GROUNDWATER MAPPING AND ASSESSMENT

A COMPARISON OF THE DANISH AND SOUTH AFRICAN APPROACHES

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0. PREAMBLE

The current project is funded by the Danish Ministry of Foreign Affairs under the Strategic Water Sector Cooperation (SSC), which is a collaboration between Denmark and South Africa with the aim of exchanging knowledge and technology to support that "water is efficiently and effectively managed for equitable and sustainable growth and development". One of the objectives of the collaboration is to support South Africa in their efforts to obtain a long-term, sustainable utilisation of groundwater as a water resource.

The project has been organised with a project group, a reference group and a steering committee. The project group has been responsible for analysing the South African and Danish conditions, provide recommendations and reporting. The Reference Group has provided input to the project at an initial stage and commented the analyses and reporting. Moreover, the consultants of the Reference Group have provided input through individual interviews. In addition to overseeing the project progress, the Steering Committee has provided technical input to the analyses and report through meetings and comments to the report.

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1. INTRODUCTION

Although groundwater plays a major role as a drinking water resource in rural areas and smaller towns, surface water constitutes the bulk of the drinking water supply to most larger cities in South Africa. Surface water is, however, very sensitive to weather conditions, and several contiguous dry years can lead to droughts with water shortages, as was last experienced between 2015 and 2018. While groundwater is similarly susceptible to dry periods where recharge to the aquifers is limited, the response in the groundwater system is slower providing a buffering capacity towards the year-to-year variations. A higher utilisation of the groundwater resource, which is currently evaluated to be underutilised, may thus aid in developing a water supply system that is more resilient towards future droughts.

The benefit of utilising the groundwater resource in South Africa has long been recognised and much more so in the last 10 years with several national strategies having been formulated, with the aim of enhancing the use of the resource. However, with the resource playing a smaller role in terms of total volume compared to surface water, its utilisation at the national level has generally received less focus. The national strategies have not yet been fully converted into operational and standardised approaches supporting the protection and sustainable use of the groundwater resource.

In Denmark, the drinking water supply is, in contrary, 100% based on groundwater, with surface water only playing a minor role as supply for industrial use. The groundwater quality is generally high and treatment has traditionally been limited to aeration and sand filtration. Preserving a good groundwater quality is a priority among all Danish political parties and protection of the resource for current and future generation has thus been high on the agenda. This has, among other, resulted in the development of a national groundwater mapping programme initiated in 2000. The groundwater mapping programme has led to the development of a general approach used as the basis for all studies within the programme. The program has additionally funded the development of a series of guidelines for the various tasks undertaken during the studies, as well as the development of new methods, instruments and software.

The objective of the current project has been to analyse the extent to which elements from the Danish groundwater mapping approach can be adapted to South African conditions. The analysis is based on a description of the approaches currently used in the two countries (Chapter 2 and 3) followed by an identification of key factors of the two approaches that are compared in Chapter 4, followed by recommendations from the project in Chapter 5.

2. THE DANISH GROUNDWATER MAPPING APPROACH

2.1 Background

Nearly 100% of Denmark’s water supply is based upon groundwater. Traditionally, the water supply has been focused on a simple treatment process consisting of aeration and a simple sand filtration. As the water supply was based fully on groundwater of a high quality, other treatments including, for example, chlorination, reverse osmosis, active carbon or advances filtration, was not needed. However, particularly during the 1980’s and 1990’s, Denmark began to monitor for a wider range of pollutants in the drinking water, which were found. Thus, it was realised that protective actions needed to be taken in order to maintain the high-quality groundwater for future generations.

The Danish Groundwater Mapping Program has its roots back in 1995, when the Danish Minister of Environment and Energy asked the 14 counties in the country to designate areas of special drinking water interests. These areas were designated in order to secure a groundwater-based water supply based upon simple treatment, for future generations. The total area designated as special drinking water interests covers approximately 40% of Denmark's total area. The funding for the groundwater mapping program was agreed upon in 1999 with the establishment of the drinking water levy. The agreed levy funded the program from 2000 - 2015.

The Groundwater Mapping Program's primary focus was on the protection of the groundwater resources within the areas of special drinking water interests (SDWI) ("områder med særlige drikkevandsinteresser", OSD), as designated by the counties. These areas are the equivalent to Strategic Water Source Areas in South Africa. The counties were responsible for designating groundwater vulnerability areas within the SDWI, considering various possible sources of contamination, both human and natural. Thereafter, the counties were required to develop groundwater protection plans in order to secure the groundwater quality.

In 2007, Denmark undertook a structural reform where, amongst other regulatory and institutional changes, the counties were dissolved. At this time, the responsibility for the Groundwater Mapping Program was transferred to the state, coordinated by the Danish Nature Agency, where after upon the designation of the groundwater vulnerability areas, the municipalities were required to develop and maintain the groundwater protection plans at the local level.

In the end of 2015, the original levy expired. At this time, all the areas of special drinking water interests and the waterworks catchment areas outside of these areas, had been mapped and the vulnerable areas where actions needed to be taken had been designated. However, during the course of the Groundwater Mapping Program, it was realised that the conditions are not static, and that the program needed to continue to take into account the changing water supply structure, including increases/decreases in groundwater abstraction, new wells, wells taken out of production as well as new information on the geology and hydrology since the original groundwater mapping had taken place. Thus, in 2015, the drinking water levy was renewed in a new Act, continuing the program with a focus on updating the groundwater mapping. In these cases, the municipalities request an updating of the groundwater mapping when they have changes in their water supply structure or new information affecting the designation of the groundwater vulnerability areas that the municipalities need to protect.

2.2 The Danish Setting

2.2.1 Danish legislation

This section provides a brief description of the relevant laws governing the administration of the groundwater resources in Denmark.

The Danish Water Supply Act was drafted to secure the use and protection of Denmark's groundwater resources based upon a unified planning and quality limits for drinking water. It is this Act that the gives the basis for the Danish Groundwater Mapping. Here, the Danish EPA is required to designate the areas of special drinking water interests, define the drinking water catchment areas, designate the areas that are particularly vulnerable to different types of pollution where groundwater protection plans need to be developed and to designate the well-head protection areas. Other relevant paragraphs of the Act include:

- Municipalities are required to create groundwater protection action plans.
- Municipalities are required to develop water supply plans.
- Municipalities have the authority for abstraction permits
- Municipalities are required, once a year, to submit abstraction and water quality data to the national groundwater database, Jupiter.

- Municipalities have the responsibility to make sure that the waterworks are meeting the water quality and reporting demands.
- All water wells need to be reported to the Geological Survey for Denmark and Greenland, including all geological and hydrological data collected under the establishment of the well.

Under the umbrella of the Danish Water Supply Act, there are a number of auxiliary Acts, where the ones relevant to groundwater protection include:

- The Water Levy Act, which provides the funding for groundwater mapping in Denmark. The Act states that every waterworks supplying drinking water to more than 10 households pays a levy, on a per cubic meter price, that is specifically earmarked for groundwater mapping and assessment.
- Act on the assessment of well-head protection areas, where the municipalities evaluate the vulnerability of these areas with respect to nitrate and pesticides, and whether or not restrictions in these areas need to be taken.
- Act on water quality and control at the waterworks, which sets the drinking water limits and dictates the control program that the waterworks are required to conduct.
- Act on groundwater protection action plans, which provides the requirements of the contents and detail of the plans which the municipalities are required to produce.
- Act on water well drilling and decommissioning, which directs how wells are to be safely drilled or plugged, preventing pollution from reaching a deeper groundwater aquifer through a leaking borehole.

Environmental Protection Act provides much of the teeth to groundwater protection. The Act provides municipalities the authority to restrict or prohibit activities that could endanger the water quality in current or future water supply wells. The Act can be used to implement the groundwater protection action plans with respect to nitrates and pesticides. The Act dictates that voluntary agreements should be made, but if that is not possible, the municipality can issue an injunction forcing an agreement. The Act dictates that all affected parties need to be fully compensated for any monetary losses.

Soil Pollution Act was drafted to prevent pollution from point sources from having a negative impact on the groundwater quality, human health and the environment.

As governed by Danish legislation, the different responsibilities for groundwater protection are shown in Figure 1.

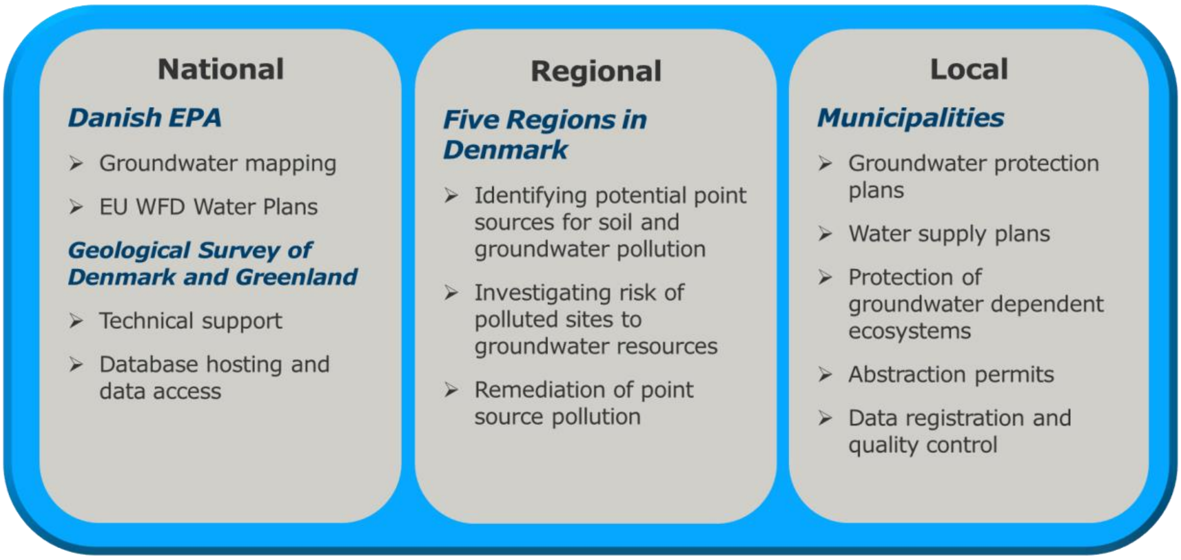

Figure 1 Responsibilities for groundwater protection on the national, regional and local level.

2.2.2 Water supply and distribution

In Denmark, the government owns the rights to the groundwater resources, and thus any utilisation of groundwater requires a permit. The only exception to this is for single households, who can establish their own well, as long as they don't have a possibility to be connected to a water supply distribution net. Groundwater use is generally divided in the following categories:

- Municipal and private waterworks, supplying more than 10 households,
- Smaller waterworks supplying 3 – 9 households
- Single households
- Industry
- Institutions, including day care, schools, hospitals, etc.
- Agriculture, including field irrigation, plant nurseries, orchards, vineyards, etc.

It is only the municipal and private waterworks that have to pay the drinking water levy. The other uses only have to pay for the costs of production and distribution.

According to the national statistics, in 2019 there was withdrawn 708 million m^3 groundwater, where 59% went to municipal and private water supply, 32% went to agriculture, and 9% for industrial use.

The municipalities are responsible for the permits. During the permitting process, the municipality considers water quality required, the amount asked for in respect to groundwater recharge (sustainable use), impacts on groundwater dependent ecosystems, and impacts on existing groundwater abstraction.

The drinking water supply in Denmark is based on a decentralised structure, containing both private and municipal water supply companies. The private water supply companies tend to be smaller waterworks, with production under 200,000 m^3/year established for smaller towns and villages. The municipal water supply companies are owned by the municipalities, however, operated independently. Municipal water suppliers tend to be larger, generally with production over 200.000 m^3/year. In recent years, there has been a tendency for the smaller waterworks to merge or be taken over by the municipal water supply companies.

Each water supply company, both private and municipal, has its own distribution area, where it has the responsibility to supply water to all residents who want to connect to the distribution system. The municipalities define the boundaries of the water distribution areas in a municipal water supply plan. The water supply companies are independent of each other, however, most have auxiliary connections with neighbouring waterworks, where both treated and untreated water can be exchanged. These connections are important in cases where a waterworks is not able to supply the needed drinking water themselves.

The responsibility for control that the waterworks are maintaining the drinking water quality demands and meeting the terms in their water permits, falls with the municipalities. All water works are required to report how much water they have pumped up once a year. In addition, they are required to measure water levels in their wells and take water quality samples directly from the water wells. The time interval of these measurements varies dependent upon the waterworks size and terms in their permit. All of the collected measurements are sent by the waterworks to the municipalities, who then approve the data and report it to the Danish EPA and enter it into the national groundwater database.

2.2.3 Geological and hydrological setting

The Danish geological setting consists primarily of Quaternary sediments underlain by Tertiary to Cretaceous sediments. The Quaternary sediments were primarily deposited during the several episodes of advancing and retreating of the Scandinavian ice sheet. This has resulted in a complex structure of unsorted clayey tills with lenses of outwash sands and gravels, with the sediments from older glacial events are overrun or eroded by the advancing ice sheets. This has created a setting where you have sand and gravel aquifers of varying thicknesses and area surrounded by clayey till aquitards. The thickness of these lenses tends to be 2 to 10 meters, but can be as thick as 20 to 50 meters. The south-western part of the country was not covered by the last ice advance and consists of a large outwash plain from the melting ice sheets. Here the unconsolidated sands and gravels are right at the surface, often over 50 meters thick. In addition to the glacial sediments, there are also locally interglacial and post-glacial sediments. These tend to be marine sediments and lake bottom sediments. The thickness of the Quaternary sediments varies widely, from just under 2 meters thick in the eastern part of Zealand to about 120 – 150 meters thick in the central part of the country.

The Pre-Quaternary sediments include the Miocene sandstones and shales, Oligocene shales, Eocene diatomite and shales, Palaeocene shales, marls and limestone, and Cretaceous Chalk. The Miocene sandstones form the Pre-quaternary aquifer in southern Jutland, whereas the fractured limestones form the Pre-quaternary aquifers in northern Jutland and the islands of Central and Eastern Denmark.

The island of Bornholm in the Baltic Sea has a unique geological setting compared to the rest of Denmark. The island lies within the Sorgenfrei-Tornquist tectonic zone, which marks the boundary between the Scandinavian shield and the deeper basins to the west. The northern two-thirds of the island consist of granite and gneiss, whereas the southern third contain a range of sediments from Cretaceous limestones, sands and shales, Jurassic, Triassic, Silurian and Ordovician limestones and shales, and Cambrian sandstones and shales. The overlying Quaternary sediments are, in general under 20 meters thick and more often than not, less than 10 meters. As the island lies in the tectonic zone, it is heavily faulted, particularly in the Mesozoic and Palaeozoic sediments. In the granite and gneiss, the aquifers lie in the faulted fracture zones. In the southern portion of the island, the aquifers are predominately fractured sandstones, with some production also occurring in fractured shales. In the south-western part of the island, there is some abstraction from Cretaceous sands and fractured limestones.

Figure 2 shows an illustration of a typical geological setting in Denmark, where you have 30 to 120 meters of unconsolidated Quaternary sediments, predominately glacial clayey tills and lenses of outwash sands and gravels, overlying the Pre-Quaternary sediments.

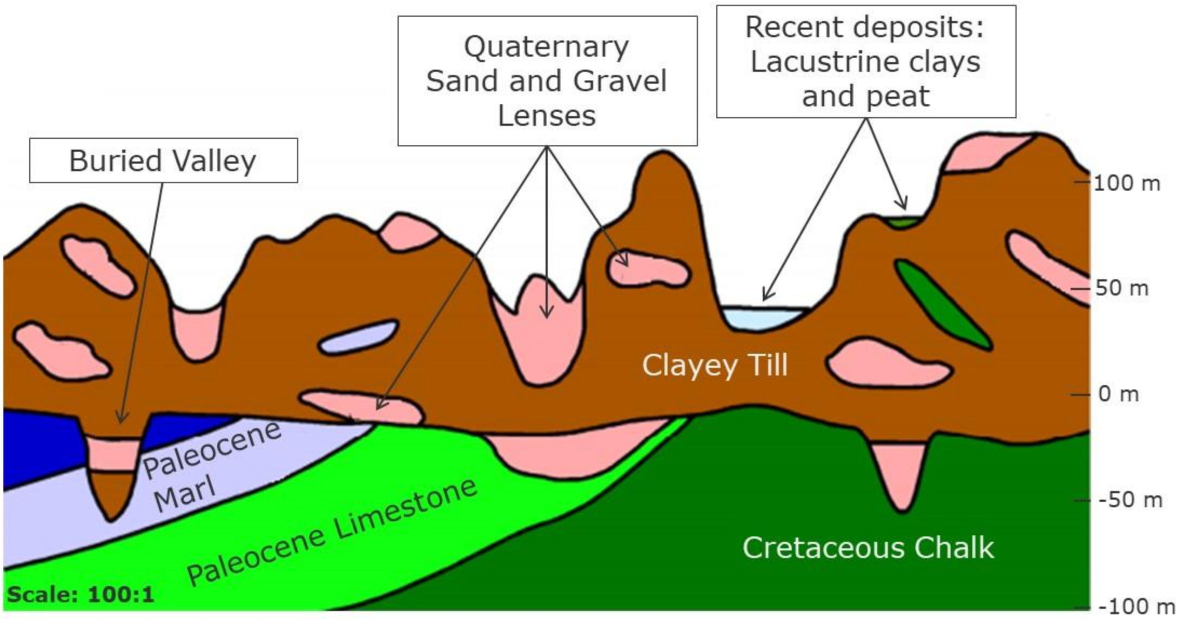

Figure 2 A regional cross-section illustrating the typical geological setting in Denmark, excluding the island of Bornholm. The figure shows the Pre-Quaternary sediments overlain by glacial sediments, predominately clayey till with lenses of outwash sands and gravel, and post-glacial lacustrine clays and peat at the surface.

Precipitation in Denmark varies from over 900 mm/year in southern Jutland, to just under 600 mm/year in much of Zealand, Lolland, Falster, Møn and Bornholm, Figure 3. However, most of the country is seeing a long-term increase in precipitation. Of the precipitation, between a third to a half of it infiltrates to the saturated zone, ranging from just over 400 mm/year in southcentral Jutland to 150 – 200 mm/year on parts of Funen, Zealand and the other eastern islands, see Figure 3. The pattern of infiltration is dependent not only on precipitation, but also on soil type, where the clayey soils in the eastern half of the country have a higher runoff potential combined with being better agricultural soils and thus higher evapotranspiration rates.

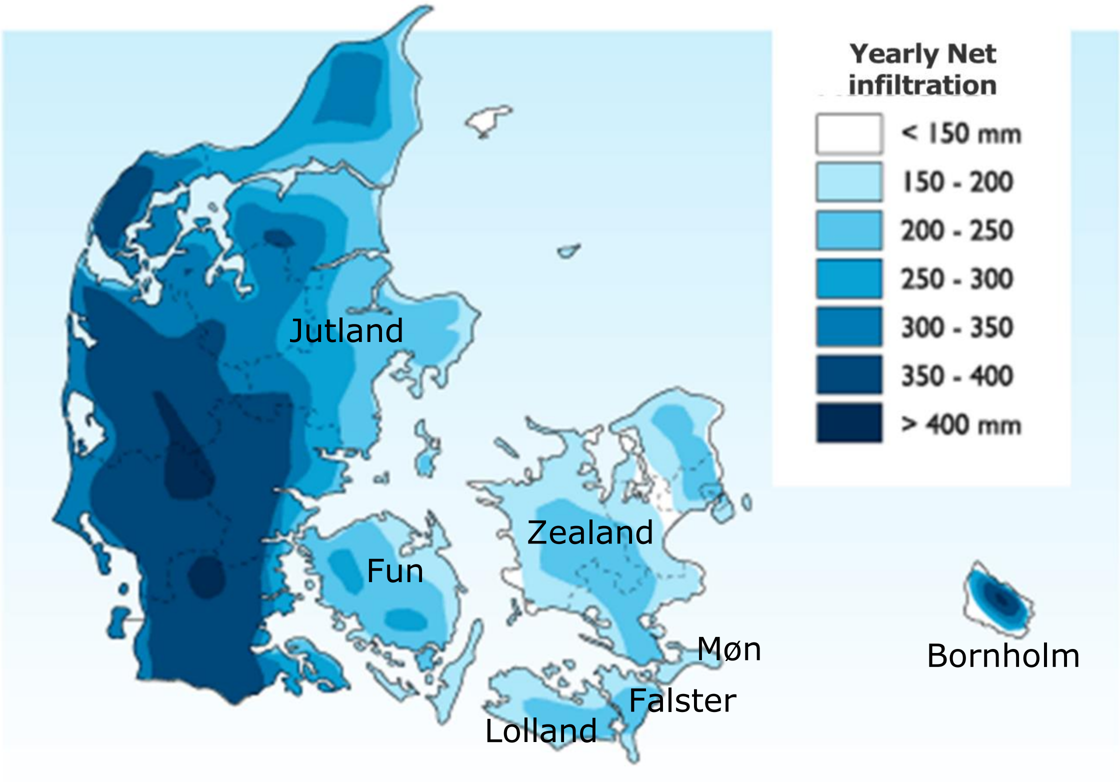

Figure 3 The yearly net infiltration to the saturated zone. Source: GEUS - https://www.geus.dk/udforsk-geologien/viden-om/viden-om-grundvand/vandets-kredsloeb.

2.2.4 Challenges and threats

In general, groundwater in Denmark is of a high quality, however, there are still a number of challenges and threats, both naturally occurring pollutants and from human sources. These have an impact on the water quality and can influence the quality of the resource for future generations.

The natural occurring pollutants that influence the Danish groundwater quality come from the sediments forming the aquifers and aquitards. Groundwater abstraction from the fractured chalk and limestone aquifer often have high concentrations of arsenic, strontium, fluoride, non-volatile organic carbon, and saltwater. These come from the natural minerals within the sediments or from residual seawater remaining in the limestone and chalk matrix from when the sediments were formed. High levels of arsenic are also seen in the Miocene shales that can seep into the quaternary aquifers where buried paleo-channels eroded through the Miocene sediments. Concentrations of these naturally occurring pollutants can potentially increase with over-abstraction (non-sustainable groundwater use), degrading the groundwater quality. In the Quaternary sediments and limestone aquifers near the surface there are also areas with high nickel and arsenic concentrations. This generally comes from the lowering of the groundwater table where particularly pyrite becomes oxidised. When the water table rises again, the arsenic and pyrite are released again into the groundwater, causing a rise in concentration. On the smaller islands and near the coasts, groundwater abstraction can also induce seawater intrusion into the groundwater aquifer, degrading water quality.

The primary source of pollution from human sources comes from agriculture. Denmark is the most agriculturally intensive country in Europe, with over 60% of its total area in agricultural production. Here, it is nitrates from fertilisers and pesticides that pose the largest problem. Areas with sand and gravel at the surface and little clay layers are particularly vulnerable to nitrate leaching from the farm fields, as there is little chance for nitrate to be reduced before it gets to the aquifer. Pesticides also pose a problem, as they are also found to leach into the groundwater. In general, only pesticides that degrade in the soils are approved for use in Denmark, and it is the now banned pesticides that compose the largest quantity of pesticides seen in the groundwater today. These pesticides were banned precisely because they are too mobile and posed a significant threat to the groundwater resources. However, there still is observed approved pesticides in some areas.

On top of the agricultural-based pollutants, pollutants from industrial sources and landfills also pose a threat to the groundwater resources. These are often point-source pollution from single sites where there were spills or has been leakage over longer periods. The most significant pollutants include chlorinated solvents, but heavy metals and BTEX can also pose a threat.

2.3 Concept and structure of groundwater mapping

The current assessment and protection of groundwater resources in Denmark are governed by three parallel processes: Groundwater Mapping, the EU Water Framework Directive (WFD) Water Plans and the regions strategies for cleaning up governing point source pollution sites.

The primary focus for groundwater mapping is to actively protect the quality of the groundwater to secure clean drinking water for all future generations. The focus of the activities in groundwater mapping is to determine where the current and future groundwater resources are and thereafter determine where these resources are vulnerable, and actions need to be taken in order to protect these resources. The focus of groundwater mapping is on the local scale.

The focus of the WFD Water Plans is to determine the quantitative and quality conditions of the different regional aquifers. The WFD requires groundwater to have a good quantitative and quality status. The Water Plans do not just cover groundwater, but also deal with surface water and water ecosystems. Thus, a primary consideration for the quantitative status is on sustainable abstraction, determining how all groundwater uses impact the groundwater dependent ecosystems. The focus on these calculations is on the regional scale.

The focus of the point source pollution program is to determine where there are sites that may be polluted resources and examine the extent that these sites threaten the groundwater quality in the areas' aquifers. If the sites are determined to be a significant threat to groundwater resources, then remediation activities to remove both the source and clean the polluted groundwater are undertaken. These activities are conducted by the Danish Regions, with the results from the studies used by the municipalities in their water planning and permitting.

Figure 4 shows a diagram illustrating the three separate processes for groundwater mapping and assessment in Denmark. The first two programs are run by the Danish EPA, whereas point source pollution programs are undertaken by the Danish Regions. The end recipient of the results of all processes are the municipalities, who are required to take the necessary measures for the groundwater protection. Results from all processes are implemented in the different protection plans and permitting to ensure that both the groundwater quality, quantity and groundwater dependent ecosystems are protected.

In this section, a detailed description of these three programs is provided.

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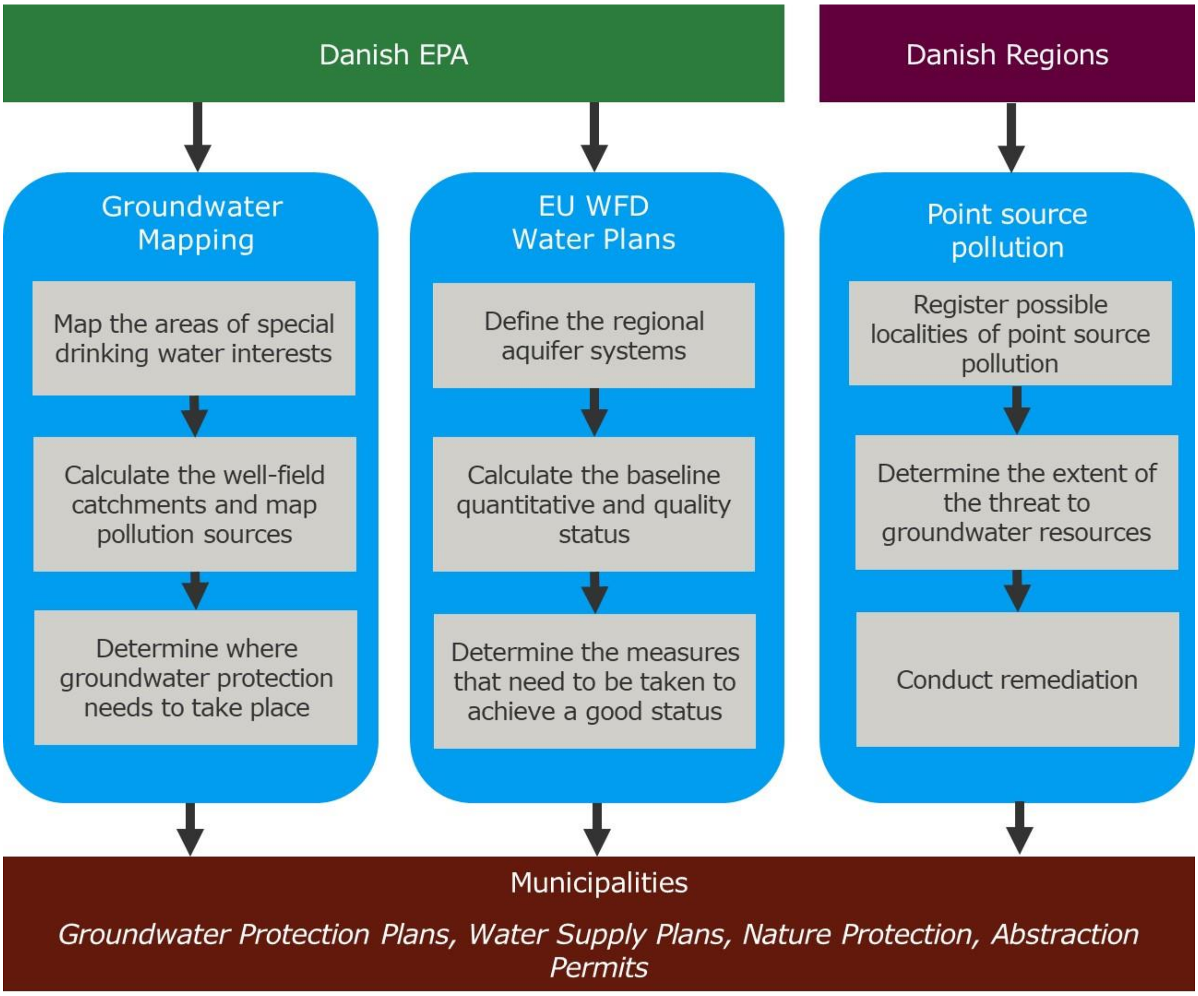

Figure 4 Diagram outlining the two parallel processes for groundwater mapping and assessment in Denmark.

2.3.1 Groundwater Mapping

The Danish Groundwater Mapping Program has been conducted over two different phases: the first phase was from 2000 to 2015, with the second phase beginning in 2016 (Danish EPA, 2022). During the first phase, the primary focus was on mapping all of the areas of special drinking water interests, covering about 40% of Denmark's total area. In addition, well field catchment areas outside of these areas were also mapped. In 2016, the focus changed, where the existing mapping is updated in the areas where there was a change in the location or amount of groundwater abstraction conducted by the waterworks, or where new information can influence the designation of the groundwater vulnerability areas where municipalities have to develop groundwater protection action plans.

Although the focus between the two phases has shifted from mapping all areas to updating where there are changes, the actual mapping process is largely the same. The process involved is illustrated in Figure 5. The process includes the following five steps:

1. Screening
2. Start
3. Data
4. Results
5. Completion

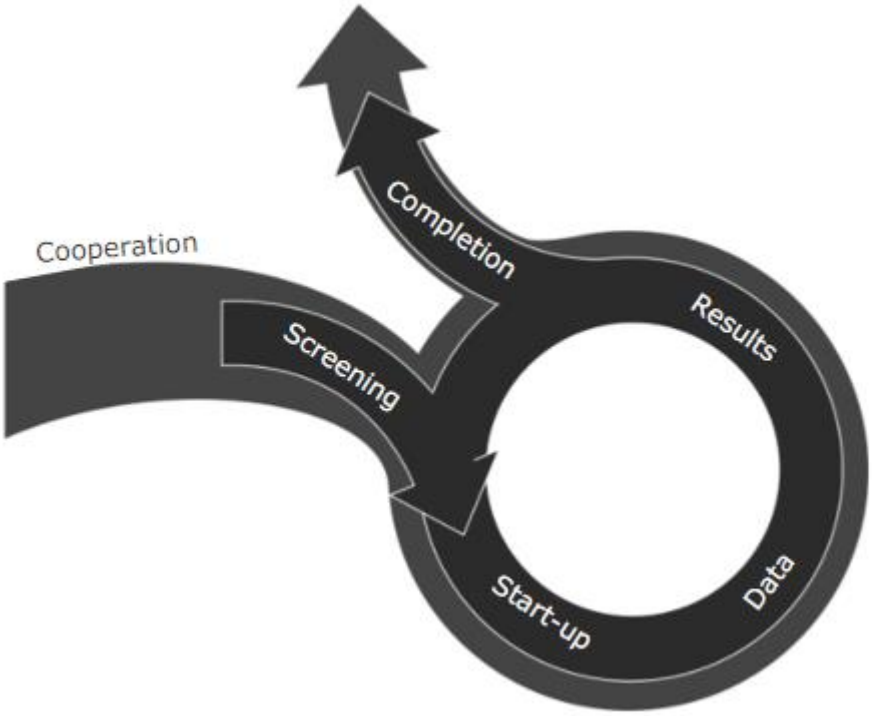

Figure 5 Diagram illustrating the processes involved in groundwater mapping. Modified from Danish EPA (2022).

The diagram is drawn as a circle in the middle to illustrate that groundwater mapping can be an iterative process. The ideal succession is to go through from Screening, through Start-up, Data and Results, ending with the Closing phase. However, there can be situations when, during the Results phase, it is discovered that an important information is missing, and certain parts of the mapping need to be looked at again. It doesn't mean that the entire process needs to be redone, but that the considerations along the mapping process are re-evaluated. Then, when the process is completed to the needed quality, the mapping is closed.

2.3.1.1 **Screening**

The groundwater mapping process begins with a dialogue between the Danish EPA and the municipalities. The municipalities determine they have a need for a new mapping, they submit a request to the Danish EPA. These changes can be an increase or decrease in one or more waterworks permit amount, new wells that have been drilled or wells taken out of production, or new data or information which could affect the results of the groundwater mapping from the first phase. These submissions are then prioritised by the Danish EPA with respect to the type of request submitted and the resources available to conduct the new mapping activities. Once the submissions are prioritised, the municipalities are notified as to the results of the screening and when the new mapping activities will begin.

2.3.1.2 **Start-up**

Start-up begins directly after the screening process. This consists of a desk top study, where the primary purpose is to obtain a detailed overview of existing data, models and previous groundwater mapping activities. These data, models and activities are then reviewed and analysed to determine where there are gaps that need to be filled in the next phase of groundwater mapping, which takes place in the Data phase of the project. Start-up thereafter concludes with recommendations to how these data gaps can be filled, taking into consideration the objectives of the specific groundwater mapping area.

The first step in Start-up involves the collection of all existing data, models and reports. This includes:

- Waterworks data, including abstraction rates, active wells, and monitoring wells.
- Geophysical data, including all studies conducted in the area. This can be resistivity surveys, areal electromagnetic surveys, magnetic resonance surveys, seismic lines, and borehole geophysical logs.
- Geological data, particularly from boreholes, maps and reports/articles.
- Water quality data.
- Hydrological data, including water level measurements, aquifer potential maps, pumping tests, measurements from data loggers, stream measurements.
- Reports and databases from previous groundwater quality studies.
- Existing 3D digital geologic and hydrostratigraphic models, with the documentation.
- Groundwater and hydrological models, with the documentation.
- Land use data and mapped polluted localities.
- Any relevant reports on studies conducted in the mapping area.

Once the data is collected, it is evaluated with respect to the quality and spatial coverage of the data. For example, the geophysical data is evaluated with respect to the age of the data and how well the results can reveal the geological formations in the area. The spatial coverage is then evaluated on the background of where we have good, moderate, poor and no data. Once the quality and special coverage of each data type has been evaluated, the data gaps are identified and recommendations for further data collection are made. This could be in the form of a synchronous water level measurements across the area or the collection of more geophysical data.

For groundwater quality, the reports are reviewed to determine the state of the aquifers at the time they were mapped. This is then evaluated against the parameters and techniques used today to determine if there are any gaps that need to be filled. For example, there are several new pesticides that are analysed for today in comparison to studies taken place 10 years ago. In addition, the results from the previous studies are compared with newer results to determine how much has changed. From this, recommendations are provided regarding which water quality parameters need to be addressed in the new mapping.

Geologic and hydrostratigraphic models are evaluated on two different levels. The first is an evaluation on how well they still fit with regards to evolution of the conceptual geological model of the area. In the time since the geologic or hydrostratigraphic model was produced, there may have come other studies that have changed the understanding of the area; for example, there may have been mapped new faults, buried valleys or additional aquifers that were not included in the existing geological or hydrogeological model. The second level is how well the existing digital model fits the collected data. There often will have come new data in the time since the geologic or hydrostratigraphic was constructed. The model is therefore evaluated against the collected data to determine the quality of the model. Based upon the two levels of evaluation, recommendations for updating or creating a new geologic or hydrostratigraphic model are made.

Groundwater and hydrological models are evaluated with respect to their quality and how well they will be able to simulate the groundwater flow system in the mapping area. This includes an evaluation with regards to their hydrostatigraphic framework, how well they simulate water levels (both in boreholes and potentiometric maps), geographic distribution of errors and surface water. From this, recommendations are made as to whether the model can be used as is, needs to be updated, or a completely new model needs to be set-up.

The final evaluation in Start-up looks at the designation of groundwater vulnerability areas. During the course of the groundwater mapping program, the methods for designating the groundwater vulnerability areas has varied from county to county, first becoming fully standardised in 2012. Thus, these primary focus on the evaluation of the groundwater vulnerability areas designated in the specific mapping area focuses on the methods used in the designation and how well they fit with the current approved standards. Recommendations are then made as to whether or not the groundwater vulnerability areas need to be updated in the new mapping.

The final product from Start-up is a summary of the recommendations of the tasks that need to be conducted during the Data phase of mapping. Start-up produces a full list of tasks that are categorised either as essential or non-essential. For the non-essential tasks, an evaluation of how they can improve the overall results of the groundwater mapping are provided, so that decisions can be made whether or not there is time and resources to conduct these tasks.

2.3.1.3 **Data**

The Data phase of groundwater mapping consists of groundwater mapping activities that needed to fill the gaps identified under Start-up. The activities that are conducted are determined at the beginning of the Data phase of the project, considering the primary objectives of the groundwater mapping, available time and particularly available budget.

There are four overarching tasks under the Data phase: supplemental data collection, geological modelling, groundwater quality modelling, and groundwater modelling. The tasks, workflow and data exchange for the Data phase is presented in Figure 6. In the figure, the numbers show the overall workflow, though there can be overlap between the start and finish of the different tasks. In addition, when updating a mapping area, it may not be necessary to complete all of the tasks, as determined in the Start-up phase.

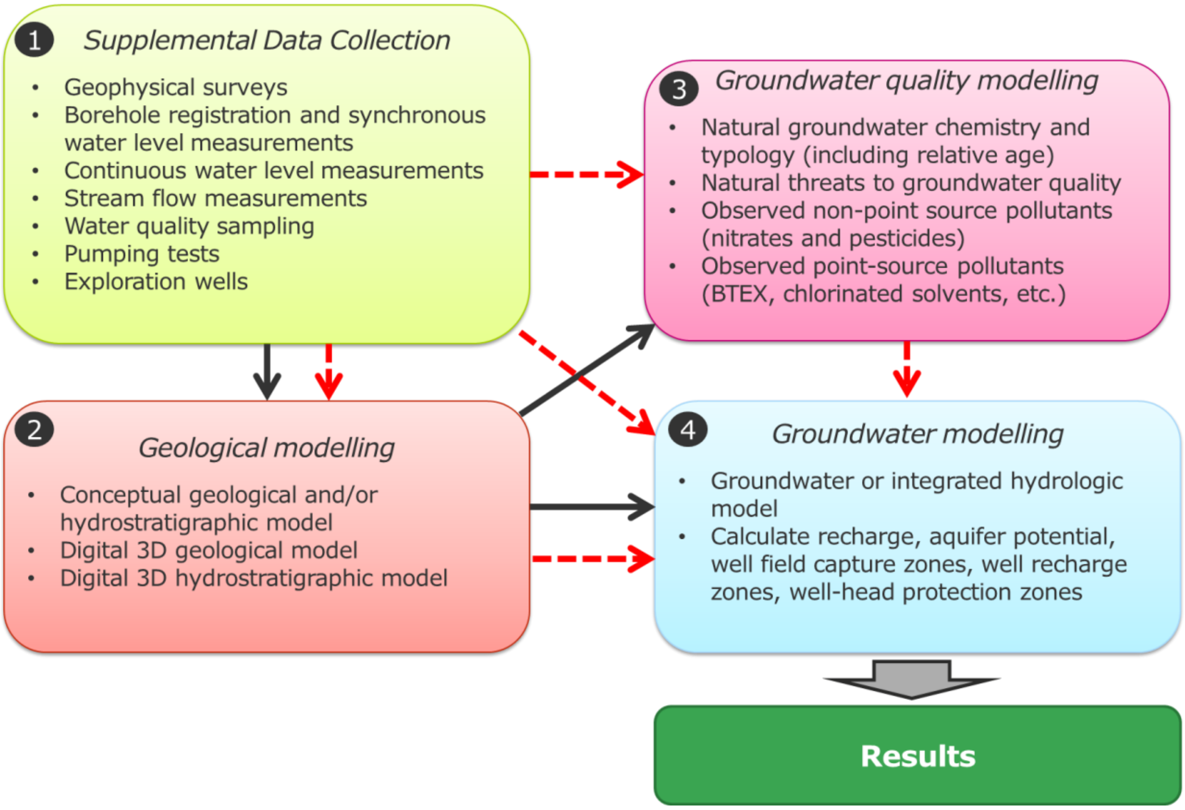

Figure 6 Illustration of the four tasks included in the Data phase of groundwater mapping. The black arrows illustrate the workflow and the red dashed arrows shows the data flow between the four steps.

Supplemental data collection:

The collection of supplemental data fills in the identified gaps. The typical types of supplemental data include:

- Geophysical surveys
- Borehole registration and synchronous water level measurements
- Continuous water level measurements
- Stream flow measurements
- Water quality sampling
- Pumping tests
- Exploration wells

In the Start-up phase, the data gaps are identified and prioritized with respect to how critical they are needed in order to complete the mapping objectives. Not all data types listed will be collected in a specific mapping project, as there can already be adequate data coverage or simply not be enough funds or time to collect the data. In addition, there may only be a portion of the mapping area that the data needs to be collected.

Geophysical surveys used in groundwater mapping include:

- Resistivity methods, such as aerial electromagnetics (AEM), transient electromagnetics (TEM), multi-electrode profiling (MEP), and single point electrode profiling (Wenner and Schlumberger).
- Seismic surveys
- Magnetic resonance sounding (MRS)
- Borehole logging.

The resistivity methods are used to help with the interpretation of the geology of the area. They are particularly useful when there are high resistivity contrasts in the sediments. In Denmark, this is typically to determine the difference between clayey units (low resistivity) and sand and gravel or limestone units (high resistivity). On Bornholm, resistivity can be used to identify bedrock, including granite, gneiss, quartzite sandstones, which tend to have a very high resistivity compared to the overlying clayey tills. In addition, the resistivity can be used to look at saltwater intrusion, as resistivity in aquifers will fall as salinity increases. Generally, the depth of investigation varies from around 50 to 80 meters in MEP and towed-TEM, to up to 500 meters with AEM and single point electrode profiling; the total depth of penetration is dependent upon the local geological conditions and groundwater salinity. Each type has certain advantages, such as AEM, which is flown with a helicopter, can cover large areas quickly, however, is more expensive and is generally restricted to larger projects. MEP and towed-TEM are conducted on lines, which provides high resolution 2D sections. Figure 7 shows an example of resistivity data from an AEM survey, with the interpreted geology. The geology along the cross-section can be interpreted using the changing colours representing the resistivity (low resistivity in blue, with progressively higher resistivities in green, yellow and orange, with the highest resistivity in red). In this case, the resistivities clearly show the Danian Limestone in the lower part of the figure, which is a fractured limestone aquifer with fresh water.

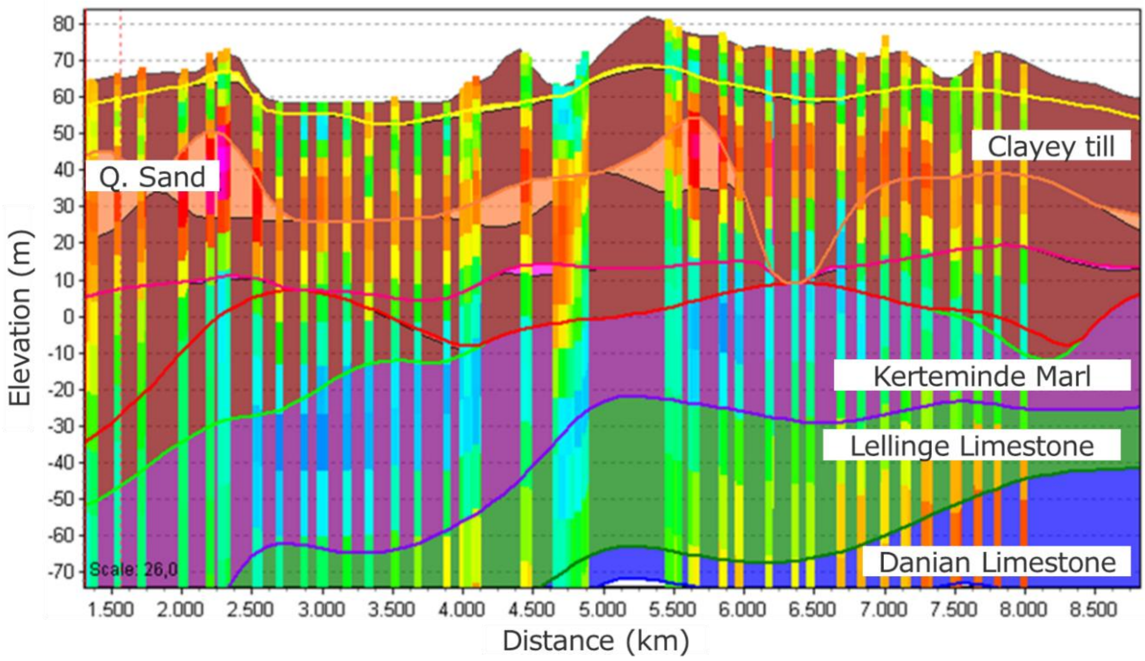

Figure 7 Example of the interpretation of AEM resistivity data. On the figure, the red colours show the more resistive units, including sands and gravels and the fractured limestone aquifers. The light orange, yellow, and green colours show the clayey till, where the higher the clay content, the more blue the colours will be. This cross-section is in an area where there is no borehole data within 500 m of the cross-section line.

Seismic surveys are employed in Denmark in order to map out the location of faults and buried valleys. Vibration seismic survey consisting of a truck with a vibrator followed by an array of geophones up to 200 meters long, can map out reflective surfaces to depths of up to 1000 meters. Magnetic resonance sounding (MRS) is a method that can be used to estimate water content and permeability in the different units to depths of up to about 100 meters. MRS uses the same technology as MR-scans used in hospitals. Borehole logs provide detailed information on the geology in a well, as well as information on the borehole construction and quality (identification of possible leaks). Flow logs are used to identify where groundwater is entering through the screened interval, which is very useful in fractured aquifers.

The primary purpose for borehole registration is to accurately locate the boreholes that can be used for water level measurements, groundwater sampling and borehole logging. In this task, the boreholes are localised and measured with GPS to obtain accurate coordinates. In addition, the overall borehole quality is assessed, where possible leakage from the surface to aquifers through the boreholes are registered. The borehole at the surface is also typically photographed, with water level measuring point identified and registered, so that the same measuring point is used in the future.

Often in association with the borehole registration, there is also conducted synchronous water level measurements across the mapping area. The measurements, often of over 100 wells, are conducted within a 14-day period in order to get a real-time picture of the groundwater potential in the aquifers. This allows the construction of groundwater potential maps that can then be used to validate groundwater models.

In order to supplement the water level measurements, data loggers are installed in boreholes in order to provide a continuous measurement of the groundwater levels. This provides high resolution data, where seasonal variations in the groundwater potential can be easily observed, as well as seeing how the aquifer responds to precipitation events. Typically, the data loggers are installed for a year or more, in order to cover a full season. The data is then used to validate the seasonal variation in groundwater levels simulated with the groundwater model.

Stream flow measurements are taken in order to quantify the stream run-off, and is used directly in integrated hydrological models. In Denmark, there already is an established network of stream flow monitoring stations which provide continuous measurements that can be used in the models, and thus this task is not often needed.

Water quality sampling is conducted in areas where there is either a spatial or temporal gap in the available data. As all waterworks are already required to do regular water well sampling, sampling conducted in groundwater mapping will tend to be private boreholes for individual households, irrigation wells or industrial wells. The wells that can be sampled are identified during the borehole registration. The sampling can be broad, covering a large range of parameters, or specific to a particular parameter important for the groundwater quality modelling of the mapping area.

Pump-tests are conducted in areas where there is a need to determine an aquifer’s transmissivity. This provides direct input in the hydrological model. Long-term pump tests can also be conducted to determine the distance to hydrological barriers, which can aid in the hydrostratigraphic modelling, particularly in areas where there are buried valleys cutting the Pre-quaternary units or areas that are faulted.

Exploratory boreholes are established in areas where there are very few boreholes providing very limited knowledge of the geology, water levels and water quality of the areas. In general, there is a relative dense coverage of borehole data in Denmark. This, combined with the high costs associated with establishing a new borehole, means that this task is not often utilised in groundwater mapping.

Geological Modelling:

In this step of the groundwater mapping, the aquifers and aquitards of the mapping area are defined and mapped out. This is accomplished in a three-step process:

1. Development of a conceptual model
2. Development of a 3D geological model
3. Development of a 3D hydrostratigraphic model

The conceptual model is the process where an overview of the area's geology is obtained and presented. It is in this stage where the mapping areas aquifers and aquitards are defined. This is conducted by going through previous reports, articles and maps, as well as primary data from key boreholes. In this stage, the general geology of the area, including stratigraphy, structures and depositional environments, are described and presented in illustrative cross-sections or sketches. Figure 8 shows a typical example of a cross-section that illustrates the conceptual model for a mapping area in central Jutland. In the figure, it can be seen that the geology of the area includes Eocene, Oligocene and Miocene units comprised of interbedded shales and sandstones, overlain by the Quaternary outwash sands and gravels and clayey tills. An important point in the conceptual model is the presence of buried valleys in the area, where streams from the Quaternary period have cut into the Pre-Quaternary units, and later filled with sands and gravels or clayey till. This provides critical input to the creation of the 3D geological and hydrostratigraphic model, as it shows the different units and structures that need to be accounted for when the 3D geological and hydrostratigraphic models are developed.

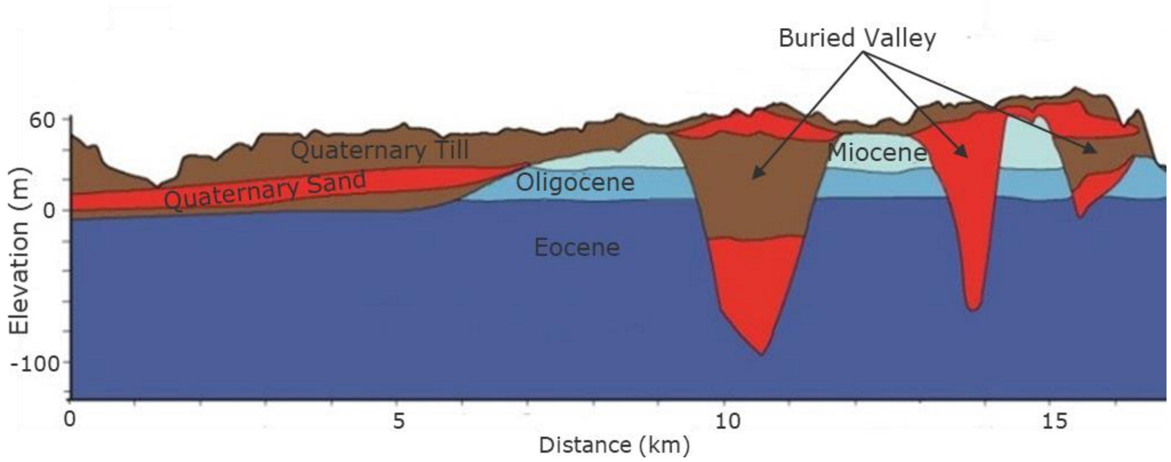

Figure 8 Conceptual cross-section of a mapping area in central Jutland. On the profile, the general geological layers are shown, including the Pre-quaternary units in blue, and the Quaternary glacial sediments shown in brown (clayey till) and red (outwash sands and gravels). The presence of buried valleys is illustrated on the cross-section.

The second step in the geological modelling process is the development of a digital 3D geological model. The model is based upon the conceptual model developed in the first step, while integrating all available data, including maps, borehole data and geophysical data. The model is set up with the aid of geological modelling software, such as Leapfrog or GeoScene3D, where the latter has been partly funded by the Danish groundwater mapping program and by far the dominating geological software in Denmark. The geological model includes the modelling of the different formations and ages, and takes into consideration the depositional, structural and tectonic history of the mapping area. For example, in Denmark, the geological model will divide the Quaternary deposits into the many different glacial advances and retreats during the Quaternary period. The geological model does not necessarily divide the units up into different aquifers and aquitards. For example, as shown in Figure 8, the Miocene, Oligocene and Eocene units are mapped out as individual formations, but within these units will be both sandstone aquifers and shale aquitards.

The third step in the geological modelling process is the development of a digital 3D hydrostratigraphic model. This is based upon the digital 3D geological model, where the geological units are divided up into aquifers and aquitards, dependent upon their hydrogeological properties. In some cases, this will include a further division of the formations mapped in the geological model, and in other cases, it can be a simplification where several formations can be grouped together. For example, in the case of the Pre-Quaternary units shown in Figure 8, they can be divided further up into mapable sandstone aquifers and shale aquitards, which can also extend across their geological boundary. An opposite example in Denmark is from the island of Zealand, where the Quaternary sand lenses are simplified to being within four units: at the surface (Sand 1), shallow (Sand 2), intermediate (Sand 3) and deep (Sand 4). In the hydrostratigraphic model, the geological units can also be divided up into fractured zones with higher hydrologic conductivity (both horizontal and vertical).

In Denmark, there has now been developed a national hydrostratigraphic model that covers all of the country, apart from the island of Bornholm and a few of the smaller islands. Therefore, the process for geological modelling has, in general, been simplified to an updating of the existing hydrostratigraphic model. In the Start-up phase, the existing model and backing documentation is reviewed and evaluated with recommendations presented. Based upon these recommendations, the hydrostratigraphic models are updated using new borehole data and geophysics that were not included in the original model, as well as errors in the model are corrected. In this way, the existing national hydrostratigraphic model is not static, but rather continuously being improved upon with every subsequent groundwater mapping project.

When the hydrostratigraphic model is completed and updated, the units mapped out provide the geological framework for the groundwater models as well as an assessment of the geological vulnerability for the aquifers.

Groundwater Quality Modelling:

The purpose of the groundwater quality modelling is to describe the groundwater chemistry observed in the mapped aquifers, including the geochemical processes and conditions, and describe how this changes geographically.

The steps in the groundwater quality modelling include:

1. Determine the processes and parameters to be analysed
2. Preparation of the groundwater quality data
3. Analysis of the important processes and water quality parameters
4. Analysis of the geographical variation of the processes and quality

The first step consists of defining the objectives of the groundwater quality modelling. In the Start-up phase, a number of recommendations are provided, however, the final decisions as to what should be completed are often dependent upon several factors that are also part of the mapping process, including (but not restricted to) whether or not new water samples will be collected, whether or not there will be a new vulnerability assessment, or the available resources to conduct the modelling. Through discussions between the Danish EPA and stakeholders, the objectives of the water quality modelling are determined.

The second step is the preparation of the groundwater quality data. As a starting point, the groundwater quality data is downloaded from the national borehole database, Jupiter. Almost all of the available water quality data will be in the Jupiter database, though there is sometimes additional water quality data which can be received from the regions, municipalities, or waterworks. Once the data is downloaded, it goes through a quality control to sort out possible sample errors. This is done by looking at the balance between the cations and anions in the water sample. If the error is greater than 15%, the sample is marked as uncertain. The parameters are then looked at closer to determine why there is a large difference and make a determination as to whether or not the water sample can be trusted. The data with the large errors that cannot be explained are either removed or marked as uncertain. The final step is to assign the samples to a specific aquifer. This is based upon the placement of the borehole's screen with respect to the aquifers mapped in the hydrostratigraphic model. In this manner, the groundwater quality can be analysed for each specific aquifer.

The analysis of the important groundwater chemistry processes is the foundation for the groundwater quality model. Looking at these processes provides fundamental information as to the relative age of the groundwater for each aquifer, how much it is influenced by activities at the surface, how the aquifer is being impacted by groundwater abstraction, and how these processes are changing through time. The primary processes that are typically analysed include:

- Groundwater oxidation state, where oxidized groundwater indicates younger, more vulnerable aquifers, and strongly reduced groundwater indicates older, less vulnerable aquifers;
- Pyrite oxidation state, where groundwater that show an influence of pyrite oxidation are younger and can indicate nitrate leaching from the surface;
- Sulphate reduction, where aquifers showing sulphate reducing conditions have older groundwater, indicating a relatively well-protected aquifer;
- Ion exchange, particularly the ratio between sodium and chloride ions, which provide information on whether the aquifer is undergoing seawater intrusion, freshening or mixing, as well as a relative age (a high sodium to chloride ratio generally indicates old groundwater);

The results from these processes are used directly in the overall aquifer vulnerability assessment conducted in the Results phase of groundwater mapping.

The final step is looking at the geographical variation of both the water quality and the processes. This is the important step in the geochemical modelling of the groundwater properties, in order to create a zoning of the predominate processes and overall groundwater quality of the mapped area. This provides critical information on where the aquifers are susceptible to pollution from the surface as well as allows to identify regions where the groundwater quality is being degraded due to pumping.

Groundwater Modelling:

For each mapping area, a groundwater model is developed. The primary objective for the modelling is:

- to calculate the well field capture zones ("indvindingsoplande")
- to calculate well head protection zones ("BNBO")
- simulate groundwater potential for each aquifer
- calculate groundwater recharge, both to the saturated zone and aquifer specific.

Both integrated hydrological models and groundwater models simulating only the saturated zone have been used in groundwater mapping. The integrated hydrological models have both a groundwater and surface water component, where input to the model includes climate data such as temperature, precipitation and evapotranspiration (based on land use). Groundwater models simulate only the saturated zone, where the input for recharge to the saturated zone used typically comes from the Danish national water resource model, which is an integrated hydrological model that covers the entire country.

Both dynamic and stationary models have been used in mapping. Generally, dynamic models are preferred, but there can be local areas where there are not data enough, either in number of time series or geographical coverage, to develop a robust dynamic model.

The models are set up, calibrated and validated specifically with respect to the four objectives stated above. The models are typically calibrated after aquifer specific groundwater level measurements and stream flow measurements. The guidelines developed for hydrological modelling provide the criteria that need to be met before a model is considered calibrated or validated.

Once the model is validated, different scenarios are simulated. As a minimum, a scenario with the maximum allowed abstraction/pumping is run (called the permit scenario). Dependent upon the mapping area and the stakeholders involved, other scenarios including no abstraction or actual/historical abstraction rates can be run. Additional scenarios to test the importance of non-calibrated input parameters, such as effective porosity, are also sometimes conducted.

The permit scenario is the model run used to supply the results used in the Results phase of the project. From the permit scenario, the administrative well field catchment areas and the well head protection zones are delineated. In addition, aquifer specific recharge and potential is calculated using the permit scenario. The well field catchment areas are calculated using particle tracking module in the models. The particle tracking module traces the movement of water from the ground surface to the well. The metadata for the particles contains the simulated travel time from model start to when the particle reaches the water well. Using this, the areas where the water infiltrates at the surface and ends up in an abstraction well, and the simulated transport time (showing the groundwater age), can be mapped. The age of the groundwater reaching each well can be calculated and plotted.

Finally, the model is quality controlled by comparing the simulated data with real data. This includes checking the simulated potential with aquifer potentiometric maps as well as simulated stream flow against measured flow. In addition, the modelled groundwater age in the abstraction wells is compared to the water quality samples to determine if there is a match between the calculated age and the observed age estimated from the groundwater chemistry. In some cases where there are modelled areas with significant differences between the calculated and simulated flow direction or age, the model is re-examined to see if these issues can be explained or if the model should be reopened for a new calibration. Thus, groundwater modelling is often an iterative process.

2.3.1.4 **Results**

When the Data phase is complete, the groundwater mapping enters into the Results phase. The geological, groundwater quality and hydrological model provides the basis for the different designations that is coming out of the groundwater mapping. These designations include:

- Well field capture zones
- Well head protection zones
- Adjustments to the areas of special drinking water interests
- Vulnerability assessments

The delineation of the well field capture zones and the well head protection zones is basically completed through the groundwater modelling conducted in the Data phase. The only activity is preparing the GIS polygons with these designations for submittal in the Closing phase. The other two activities, adjustments to the areas of special drinking water interests and vulnerability assessments combines the results from the three Data modelling activities, geological modelling, groundwater quality modelling, and groundwater modelling, in the assessments. This process is described in detail in the sections below.

Areas of Special Drinking Water Interests:

The areas of special drinking water interests (SDWI's) were first designated in 1997 and then revised in 2005. This area covers approximately 40% of Denmark's total area, and represents the area required to secure the Danish drinking water supply for future generations. These areas are in principle fixed, however, there is the opportunity to make minor adjustments based upon the results from groundwater mapping efforts.

As a guiding principle, the DSWI's were defined by areas having aquifers of high quality and of suitable size. In addition, groundwater flow in the aquifers should always be from inside the DSWI to outside, rather than from outside the DSWI's to inside. As new information from the Data phase of groundwater mapping is obtained, adjustments to the DSWI's can be made. The adjustments can include adding areas if a new aquifer with high groundwater quality is mapped. Some areas can be removed if the groundwater mapping shows that the groundwater quality is so poor that it cannot be remediated and thus used for drinking water, or if the new studies show that there is no longer a viable aquifer at that location. The boundaries can also be adjusted to prevent groundwater from outside the DSWI's from streaming into the DSWI's. These adjustments are generally made by results from the groundwater modelling.

Vulnerability Assessment:

The ultimate objective of Danish Groundwater Mapping is to identify the areas that are vulnerable to non-point source pollution. The vulnerability assessments are conducted in all areas that lie within the designated special drinking water interests or fall within a well field catchment zone outside of these interests. As stated in Section 2.2.4, the two primary non-point source threats to the Danish groundwater resources are from nitrates and pesticides. Over the last 30 or so years, there has been extensive research into how nitrates and pesticides leach from the agricultural soils to the saturated zone and thereafter flow to the aquifers that are used as a source of drinking water. The results from these studies provides the basis for the designation of areas that are particularly sensitive to nitrates as well as the areas that are particularly sensitive to pesticides and thereafter designating the areas where groundwater protection plans need to be developed.

Vulnerability with respect to nitrate

Designating the areas in which action plans need to be developed is a three-step process, as outlined in the guidelines from Danish EPA (2000) and (2021), which include:

1. Determining the aquifers vulnerability to nitrates
2. Designating the areas that are sensitive to nitrate leaching
3. Designating the areas where groundwater protective actions need to be taken.

The first step, vulnerability assessment with respect to nitrates, is based upon the sediment's natural reduction capacity. Particularly the presence of organic matter and pyrite in the aquifers and sediments overlying the aquifers, will reduce the nitrates as the flow through the sediments to the aquifer. In Denmark, it is mainly the reduced clayey sediments that have a relative high amount of pyrite available to reduce leached nitrates. The outwash sand and gravels are relative clean and will only have a limited reduction capacity. The Pre-Quaternary sediments can also have both pyrite and organic matter that can reduce the nitrates; however, the nitrate reduction capacity in these sediments is often spatially variable.

As a starting point, the determination of an aquifers vulnerability with respect to nitrates is based on the thickness of reduced clay sediments overlying the aquifer. Studies on the clay sediments in Denmark showed that the thicker the accumulative clay sediments over the aquifer are, the greater the reduction capacity and thus the better the aquifer is protected. The thickness of the reduced clay is calculated by taking the accumulated thickness of the clay layers over the aquifers from the hydrostratigraphic model, and subtracting the oxidized clay as observed in the geological descriptions from the borehole logs or alternatively the unsaturated clays. In general, if there is less than 5 meters of accumulated reduced clays there is only a limited capacity to reduce nitrate and the aquifer has a high vulnerability, if there is 5 to 15 meters the aquifer has a moderate vulnerability and more than 15 meters of reduced clays, there is a good reduction capacity in the sediments and thus the aquifer has a low vulnerability to nitrates.

There is, however, uncertainty associated with the calculation of the thickness of reduced clays, as there can be long distances between data points (borehole information) and there can be unmapped geological windows within the clay layers, providing a short cut through the protective clays and reducing the reduction capacity. Therefore, groundwater quality is also used in the vulnerability assessment. In this case, the presence of oxidized groundwater containing nitrates indicates that the groundwater in the aquifer is highly vulnerable. The presence of high and/or increasing concentrations of sulphate indicate that pyrite reduction is occurring in the sediments and that the reduction capacity within the clay layers is being depleted, and thus the aquifer is highly or moderately vulnerable. On the other hand, reduced to strongly reduced groundwater, with low and stable sulphate concentrations, often with ammonium and methane, indicates very old groundwater, and the vulnerability will be low.

Table 1 illustrates how the groundwater vulnerability with respect to nitrate is determined. Here, the thickness of reduced clay is compared to the groundwater quality. If there is agreement between these two parameters, the vulnerability is set. However, there are situations where there is not agreement between the two parameters, and an individual assessment needs to be taken. For example, there can be areas with over 15 meters of reduced clay, but one or more wells show oxidized groundwater. In this case, a closer evaluation of the groundwater quality will be taken to assess whether the oxidized groundwater can come from leakage from the surface via a damaged borehole or along a poorly constructed casing. The thickness of the clay layer will be assessed with regards to how certain the clay thickness is continuously over 15 metres or whether there is the possibility for a geological window through the clay in the area. Three-dimensional flow paths from the groundwater model are also utilised to evaluate whether the observed groundwater chemistry is a result from oxidized groundwater flowing in from a different area where the thickness of the clay layer is much less. A final decision on the vulnerability will be made based upon this evaluation. The final result is a mapping of the groundwater vulnerability with respect to nitrate, where the vulnerability for each aquifer is divided into high, moderate or low.

As an alternative to using the thickness of reduced clay sediments to determine vulnerability, a calculation of the aquifer’s natural reduction capacity can also be made. This is done particularly on the island of Bornholm, where Quaternary clay deposits tend to be thin, while the Mesozoic and Palaeozoic sedimentary rocks have a natural reduction capacity. In order to determine the vulnerability, the nitrate reducing capacity can be calculated by looking that the fraction of organic material and the presence of pyrite from samples taken from boreholes when drilled. This is thereafter compared with the water quality. If there is nitrate in the groundwater, then the natural reduction capacity in the aquifer is limited or used up, and the aquifer vulnerability will be high. On the other hand, reduced groundwater without nitrate indicates that there is a natural reduction capacity, and dependent upon the calculation of how much is present, the vulnerability will either be low or moderate.

Table 1 Designation of the aquifer's vulnerability with respect to nitrate.

Thickness of reduced clay	Groundwater quality	Vulnerability
0 to 5 meters	• Oxidised groundwater • Weakly reduced groundwater with a high sulphate content (over 70 mg/l)	High
5 to 15 meters	• Weakly reduced groundwater, sulphate over 20 mg/l	Moderate
Over 15 meters	• Strongly reduced groundwater, sulphate is under 20 mg/l (under sulphate reducing conditions), often with methane	Low

The second step in the overall vulnerability assessment is to designate the areas where the aquifer is sensitive to nitrate leaching; this is basically determining where nitrates pose a threat to groundwater quality for the specific aquifers. This evaluation takes place with respect to the aquifers that are either already used as a source for municipal drinking water supply or identified as a future reserve for the drinking water supply.

The identification of the sensitive areas for nitrates includes an evaluation of the areas where the vulnerability is either high or moderate. Areas where the vulnerability is low are determined to be adequately protected from nitrate leaching. The assessment first looks at groundwater recharge calculated from the groundwater model. The areas where there is no groundwater recharge, regardless of the aquifer's vulnerability will not be sensitive to nitrate leaching. Areas where there is groundwater recharge, and a high vulnerability will be sensitive to nitrate leaching. Areas where there is groundwater recharge and moderate vulnerability, a closer evaluation of the sulphate concentration in the groundwater is taken. If the sulphate is low (under 50 mg/l) and stabile over time, then the area is determined not to be sensitive to nitrate leaching. However, if the sulphate is high (over 50 mg/l) or has an unstable or increasing trend over time, then the area is determined to be sensitive to nitrate leaching. Table 2 provides an overview on how the areas sensitive to nitrate leaching are determined.

The third step in the process is to designate the groundwater protections areas, where actions need to take place to protect the groundwater resources from nitrate leaching. This is done by assessing the land use in the areas designated as sensitive to nitrate leaching. If the land use in these areas is already protected or in areas where fertilisers are not applied, then no protective measures with respect to nitrates needs to be conducted. This includes protected areas such as meadows, heath, bogs, grasslands and forested areas under long-term or no cultivation. All remaining nitrate sensitive areas, including agricultural, recreative and urban areas are designated as areas where actions need to be taken to prevent leaching of nitrate to the aquifers.

Figure 9 shows an example of the results of the mapping process. Note that there are large areas that have a high or moderate vulnerability but are not designated as sensitive to nitrate leaching. These are the areas where there is no groundwater recharge that reaches the aquifer. There are also significant areas that are sensitive to nitrate leaching, but not designated for groundwater protection. These are areas that are already protected from groundwater leaching (either wetlands or protected forests).

Table 2 Determination of the areas that are sensitive to nitrate leaching

Vulnerability	Recharge	Groundwater quality	Sensitive to nitrate leaching?
High	No	--	No
	Yes	--	Yes
Moderate	No	--	No
	Yes	High sulphate, unstable or increasing sulphate concentrations	Yes
	Yes	Low sulphate (under 50 mg/l) with stable concentrations	No
Low	--	--	No

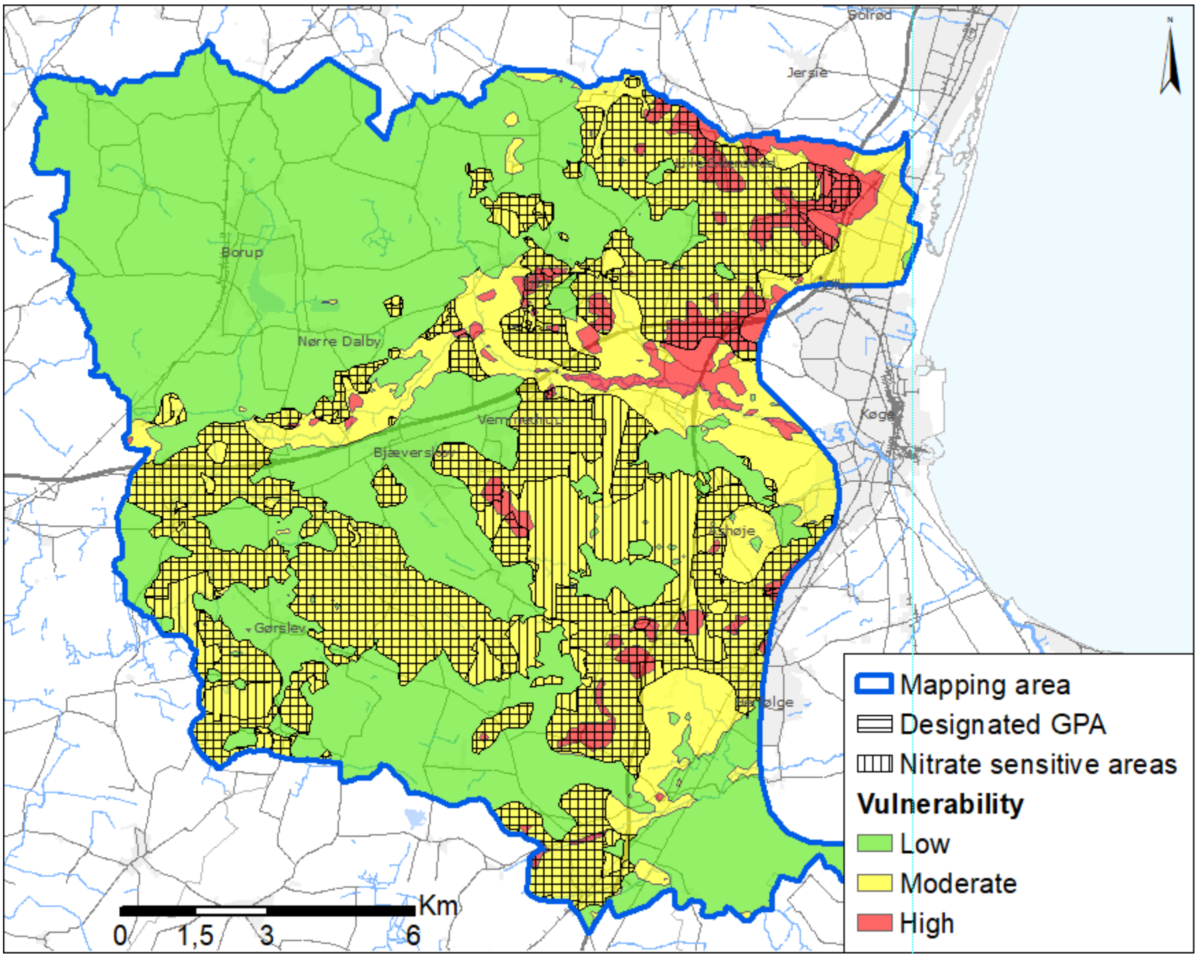

Figure 9 Example of the results from the groundwater mapping (Danish EPA, 2022). The colours represent the mapping of the vulnerability for nitrates, the vertical lines show the nitrate sensitive areas, and the horizontal lines (forming cross-hatching) shows the areas that designated groundwater projection areas (GPA).

Vulnerability with respect to pesticides

In contrast to nitrates, research conducted on the mobility and degradation of pesticides in Denmark did not produce clear cut results in determining aquifer vulnerability to the leaching of pesticides that could be used in all of Denmark. The studies have shown that for sandy soils, the vulnerability could be assessed based upon the volume of the humus and the volume of the clay and silt fraction in the soils (Danish Nature Agency, 2015). However, for clayey soils, where clay content is greater than 10%, no determination could be made, and these soils are not assigned a vulnerability.

For the sandy soils where the clay content is less than 10%, the vulnerability is assessed based upon the fraction of humus and clay plus silt in the soils. This relationship is shown on Figure 10. Based upon these fractions, the soils are divided by the researchers in four categories: Highly vulnerable (low humus and coarse grain content – cut-off shown by the red line), potentially vulnerable (soils that fall between the red and orange line), slightly vulnerable (between the orange and yellow line) and not vulnerable (soils with high humus and/or high fine grain content – soils that fall above the yellow line). From this relationship, the soil types found in Denmark are categorised into these vulnerability categories. Thereafter, maps covering Denmark can be used to designate the relative vulnerability to leaching of pesticides.

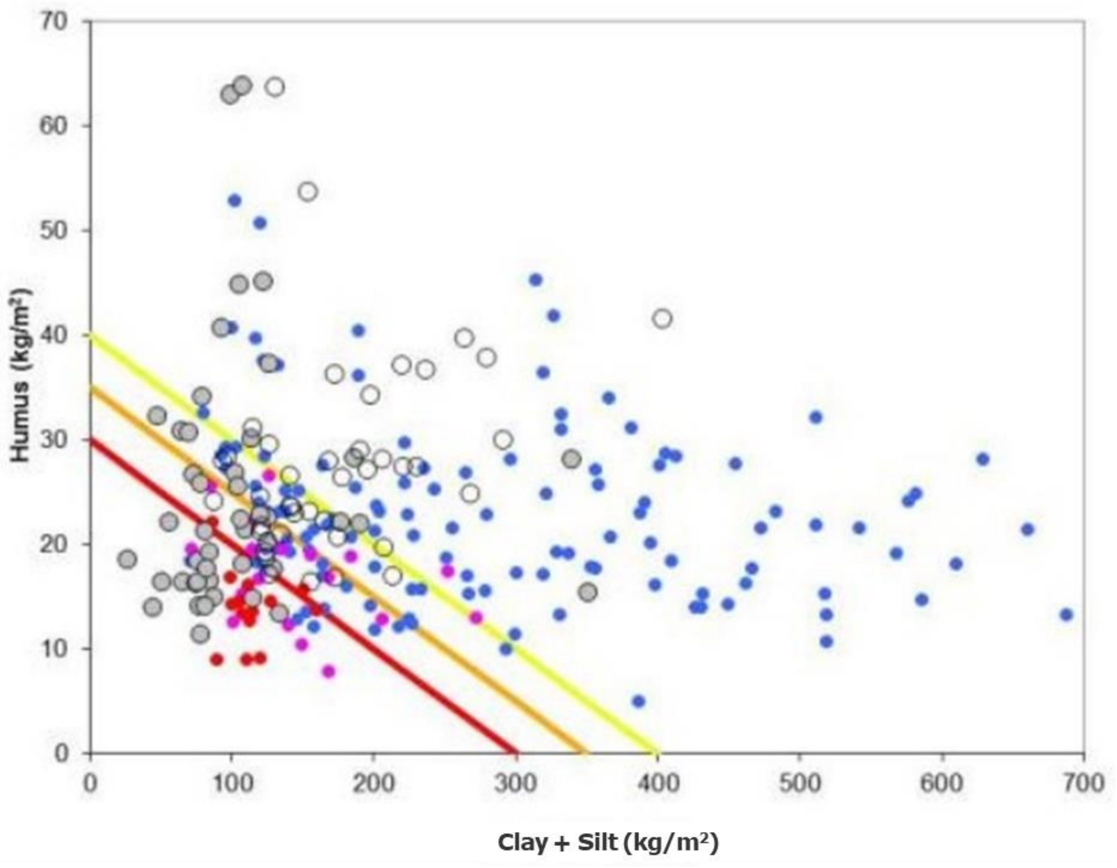

Figure 10 Relationship on the vulnerability to leaching of pesticides (Danish Nature Agency, 2015). Soils that fall below the red line are highly vulnerable, between the red and orange line are potentially vulnerable, between the orange and yellow line are slightly vulnerable, and those above the yellow line are not vulnerable.

Once the vulnerability to leaching of pesticides has been determined, the groundwater protection areas with respect to pesticides is determined. These areas include all soils that are highly vulnerable and potentially vulnerable that fall within the areas of specific drinking water interest or within a well field catchment zone for a municipal water supply. For areas with soils that are slightly vulnerable or not vulnerable, or areas that have little risk for pesticide leaching, including urban areas, road and railroads, parks, cemeteries, beaches and grasslands, no groundwater protection areas for pesticides are designated. It should be noted that for soils with more than 10% clay fraction, the results are inconclusive, and although no groundwater protection areas for pesticides are designated on these soils, it does not mean that the aquifers are protected from pesticide leaching. It means that the leaching potential in these soils could not be described, and that the soils may or may not be vulnerable to pesticide leaching.

2.3.1.5 Completion

The final stage of groundwater mapping is Completion. Upon completion of the Results phase, the four different designations are prepared and submitted to the Ministry of Environment for official acceptance. The first step includes a quality control of the submitted files. Thereafter, the designations go through an 8-week public hearing process, where there is time for all stakeholders, and the public in general, to review and comment on the designations. The Danish EPA then addresses the comments that are given. Thereafter, the designations are sent to the Minister of Environment, who then makes the designations official.

In addition, the Completion phase includes the collection and storage of the data collected during the groundwater mapping process. The results from the Data and Results phase are put in a GIS template, where the data is stored with the relevant metadata, which is subsequently publicly available. The different reports and primary data are stored in the national databases, and the geological and groundwater model is uploaded to the national model database, also for access to the general public.

2.3.2 EU Water Framework Directive Water Plans

The EU Water Framework Directive (WFD) was implemented in Denmark in 2000 to address environmental threats to the member state’s water bodies, including streams, rivers, wetlands, marine and groundwater bodies and their associated ecosystems (Danish Ministry of the Environment, 2022). The ultimate goal of the WFD is for all bodies to achieve a good status. The WFD mandated that all countries conduct a baseline analysis, create and implement a water plan by 2015. Then, every six years, a new baseline analysis is to be conducted and the water plans revised. Denmark is currently in the process of developing the next water plan for the period 2021 to 2027.

The driving force for the WFD is to protect the EU’s water bodies, so that both the freshwater and marine ecosystems remain/become healthy, and to secure clean and plentiful water resources for future generations (European Commission, 2022). Groundwater is recognized as a critical source of drinking water, supplying around 75% of the EU’s and 100% of Denmark’s drinking water. In addition, groundwater is also recognised as an important component of freshwater ecosystems, providing baseflow of clean, cool water to streams, wetlands, lakes, and coastal marine environments. Groundwater can also be a pathway for the transportation of pollutants such as nitrates and pesticides that can affect these environments. It is on this background, that groundwater is an important component of the WFD water plans developed by each country.

The WFD states, that the groundwater bodies should be assessed and managed at the river basin scale and not by political boundaries (European Commission, 2022). In Denmark, the groundwater bodies have been divided up into 23 different groundwater basins based upon the larger stream or fjord catchment areas. As Denmark only has a relatively short boundary with one neighbouring countries, namely Germany, leading to only one international groundwater basin, with the administration shared between Denmark and Germany. For each groundwater basin, three different groundwater bodies have been identified: near surface aquifers, regional aquifers, and deep aquifers. The near surface aquifers are in direct contact with the surface, and consist primarily of shallow Quaternary sand and gravel, with fractured bedrock on the island of Bornholm. The regional aquifers are larger sands and gravels deposits as well as fractured limestone, chalk and bedrock that are deeper than the shallow aquifers, but still in hydrological contact with the surface water bodies. The deeper aquifers, which include fractured limestone, chalk and sandstones, are deep enough that there is only limited hydrological contact with the surface water.

The process for each 6-year plan period includes two steps:

1. Baseline analysis
2. Development of the water plans

The purpose of the baseline analysis is to determine the current status of the groundwater bodies, both the quantity and quality. For the quantitative analysis, the risk is determined through a water balance where groundwater recharge reaching the aquifer is compared to the amount of groundwater that is abstracted from the aquifer. Taking into account the needs for groundwater dependent ecosystems, it is considered that if groundwater abstraction is greater than 30% of the recharge to the specific groundwater body, then there is a risk that a good quantitative status cannot be achieved. However, if abstraction falls below 30% of groundwater recharge, then there is a risk that a good quantitative status cannot be achieved.

The water balance is calculated using the national water resource model set up and run by the Geological Survey of Denmark and Greenland (Danish Ministry of the Environment, 2022). The model is a dynamic, integrated hydrological model, including climate data, surface water and groundwater. The model is divided up into 7 different sub-models, with the smallest being the island of Bornholm, covering an area of 589 km^2, and the largest in mid-Jutland, covering an area of 11,551 km^2. The hydrological models are based upon the national hydrostratigraphic model, which is continuously updated from the geological modelling activities from groundwater mapping. The model includes all reported groundwater abstraction and abstraction permits and is calibrated against water level and stream discharge measurements from national databases.

Figure 11 shows an example of the baseline assessment of the regional aquifers near Copenhagen. In this case, the regional aquifer north of Copenhagen (København) consists of thicker deposits of Quaternary sand and gravel, whereas in Copenhagen and extending to the southwest, the regional aquifer consists of fractured limestone. The results of the baseline assessment show that the Quaternary sand and gravel aquifer to the north has a good quantitative status (blue colour), which is in contrast to the fractured limestone that has a risk of not achieving a good status (red colour).

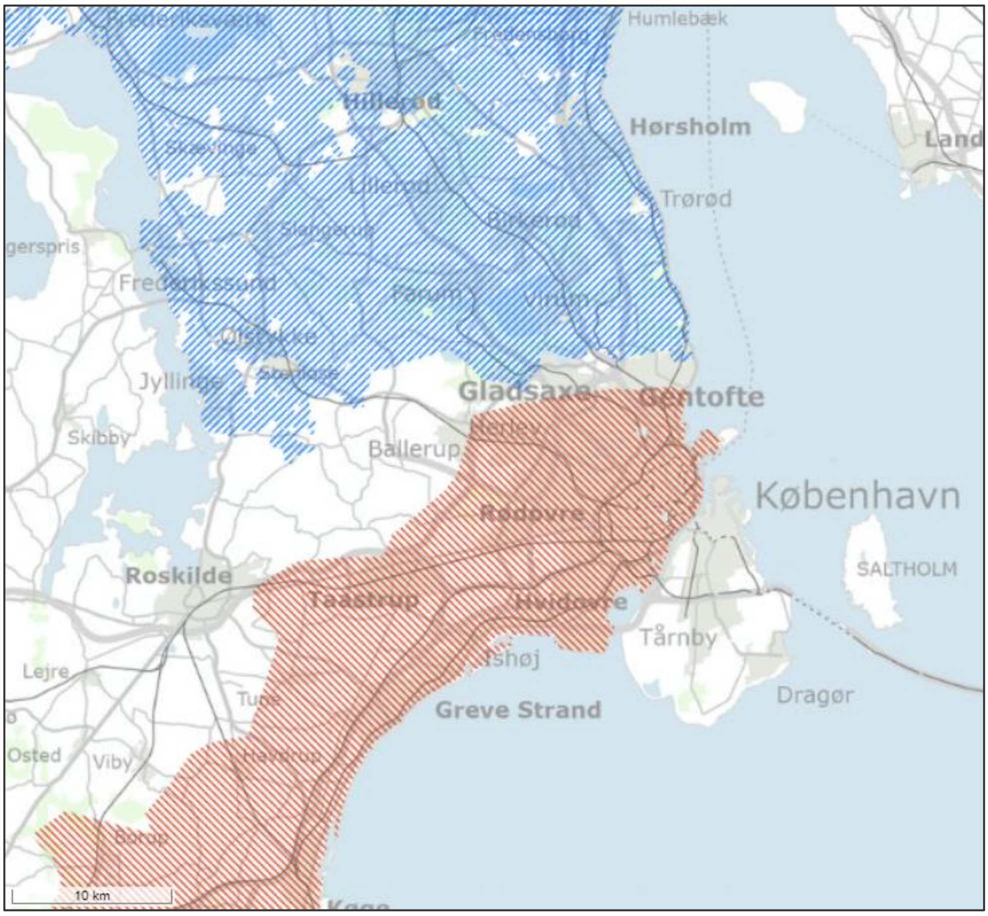

Figure 11 Quantitative baseline analysis for the regional aquifers near Copenhagen. The regional aquifer north of Copenhagen, consisting of sands and gravels, have a good quantitative status (blue), whereas the regional aquifers in and southwest of Copenhagen, consisting of fractured limestone and chalk, have a risk of not achieving a good status. From Danish Ministry of the Environment, 2022.

The calculation of the quantity status is conducted for the groundwater bodies as a whole, which contain the different aquifers. In the case near Copenhagen, both groundwater bodies cover an area of over 350 km^2 and does not take into account local variation in groundwater abstraction. Thus, when abstraction is over 30% of the recharge in a given groundwater body, there can be local areas where abstraction is not so concentrated and further abstraction can be conducted without harming the freshwater ecosystems.

The groundwater quality status looks at the broader water quality of the aquifers. In order to achieve a good status, the groundwater body should not show degradation from saltwater intrusion or exceed the groundwater quality limits. In addition, the groundwater bodies should be of a high enough quality as to not affect the groundwater dependent ecosystems or degrade the water quality in connected water bodies, including streams, lakes and the coastal marine environments.

Like for the quantitative status, the quality status is determined for the groundwater body as a whole. For example, for nitrate, if the groundwater body has one borehole where nitrate exceeds the water quality limit of 50 mg/l, it is considered to have a risk of not meeting a high standard. In these cases, a specific evaluation of the groundwater quality in the groundwater body needs to be taken.

Once the quantitative and qualitative baseline is established, the water plans are developed. This includes the formulation of the specific objectives to meet. In the water plan for 2015 to 2021, the objectives for groundwater included:

- Quantitative:
    - Abstraction over longer periods may not exceed the long-term available groundwater resource (water balance);
    - Water level cannot be reduced so that the surface water bodies cannot meet their objectives or degrade the ecological status of these or groundwater dependent ecosystems;
    - Abstraction may not result in saltwater intrusion.
- Quality:
    - Electric conductivity measurements should not indicate saltwater intrusion or other human-caused effects;
    - EU water quality limits should not be exceeded;
    - The quality should be maintained so that the surface water and groundwater dependent ecosystems are not degraded or prevented from meeting their objectives
    - Pollutants posing a threat to groundwater quality should be limited or prevented, so that groundwater quality is improved or that the long-term trend does not exceed 75% of the EU water quality limits.

Actions that are taken in order to meet the objectives sit primarily with the municipalities. This is primarily through new abstraction permits. The municipalities may not issue new permits so that the objectives cannot be met. This includes an evaluation on how the new permit will influence the surface water and groundwater dependent ecosystems and ensure that the groundwater quality in the aquifers can be maintained. In areas where there is a significant abstraction compared to recharge, use of groundwater can be prioritised, with drinking water generally taking the highest prioritisation. The Regions are responsible for determining the source for and eventual remediation of pollution from such.

In connection with the water plans, the Danish EPA monitor the water level and quality in the groundwater bodies through a national groundwater monitoring network. In addition, the state will continue to obtain new knowledge on the affects that groundwater abstraction has on freshwater and groundwater dependent ecosystems.

2.3.3 Assessing point source pollution

Since 2007, the Danish Regions have been responsible for the mapping and assessment of point source pollution in Denmark. This includes mapping all potential and actual soil pollution sites and evaluating the risk to both the surface water and groundwater resources (Danish Regions Center for Environment and Resources, 2022).

The process that the Danish Regions conduct consists of three steps: mapping all the possible sites that could potentially contain soil pollution, determining the extent of the pollution and the threat to groundwater resources, and remediation of the sites that pose a threat.

The first step is mapping all the possible sites that may be polluted. These sites can be old or current landfills, old industrial areas, leaking oil and gas tanks at petrol stations or chemical storage depots. This step is primarily done by going through old business registries and finding the different businesses that have conducted activities which may have resulted in chemical spills. This can be, for example, old factories, laundries or workshops where chlorinated solvents were used or stored, old service stations where there may have been a buried oil or gas tank, or an old landfill which is now covered over. In addition, the Regions can receive submittals from municipalities, private entities or the general public, as to other potential pollution sources. These can be, for example, old depressions in the landscape, gravel pits or clay pits that were used as unregistered landfills and thereafter covered over. These unregistered landfills can pose a particular threat as they are often covered over by the farmers after they have been filled up with containers containing chemicals and pesticides, covered with soil and now used for growing crops or grazing.

The second step is to determine the threat that the polluted sites pose to the groundwater resources. This is done through site studies, where soil samples, pore water samples, and groundwater samples are taken to see if the pollutants are present. This step can include supplemental geophysical studies, detailed geological mapping, and/or solute transport modelling, depending on the site. The product is a report which determines:

- Whether or not the site is polluted;
- The types and concentrations of the different pollutants in the soils, porewater and groundwater;
- Assessment of whether or not the pollutants at the site pose an actual threat to the groundwater resources.

In the cases where there is observed point source pollution that poses a threat to groundwater resources, the Danish Regions can go in and start remediation activities to remove the source and clean the groundwater if it is already polluted. However, as remediation is often a very expensive undertaking, the sites set for remediation are prioritized. Often, the sites are prioritised after the degree of the threat to the groundwater resources, the degree of the observed pollution, the degree that the pollution poses to a municipal water supply and whether or not there are alternative sources of clean groundwater for the affected waterworks. The actual prioritisation, though, will vary between the regions themselves.

The results from the mapping of the point source pollution at all three stages are utilised by the municipalities in their groundwater protection plans and in permitting. Many municipalities add the point-source pollution sites in their groundwater action plans in order to continue a dialogue with the region in the evaluation and remediation of particularly vulnerable groundwater resources. In addition, municipalities will use knowledge of the potential and actual polluted sites when issuing groundwater abstraction permits. For permits for waterworks, the municipalities will look at the possibility that the pollution could be mobilized and reach the drinking water well. Alternatively, the municipalities could use the results to preferentially place abstraction that does not need drinking water quality near the sites to help prevent the further spread of the pollution in the groundwater system.

2.3.4 Data flow

The data produced in the three groundwater mapping and assessment programs is publicly available and stored in different publicly accessible databases. The data in these databases is also directly utilised in the three programs as well as by the municipalities in their different groundwater management and protection activities and plans. This provides for a complex relationship between these four different activities, where each provide certain information, and each utilize information from the other programs. Figure 12 illustrates the relationship in the data flow between the programs. This flow is also described in the text below.

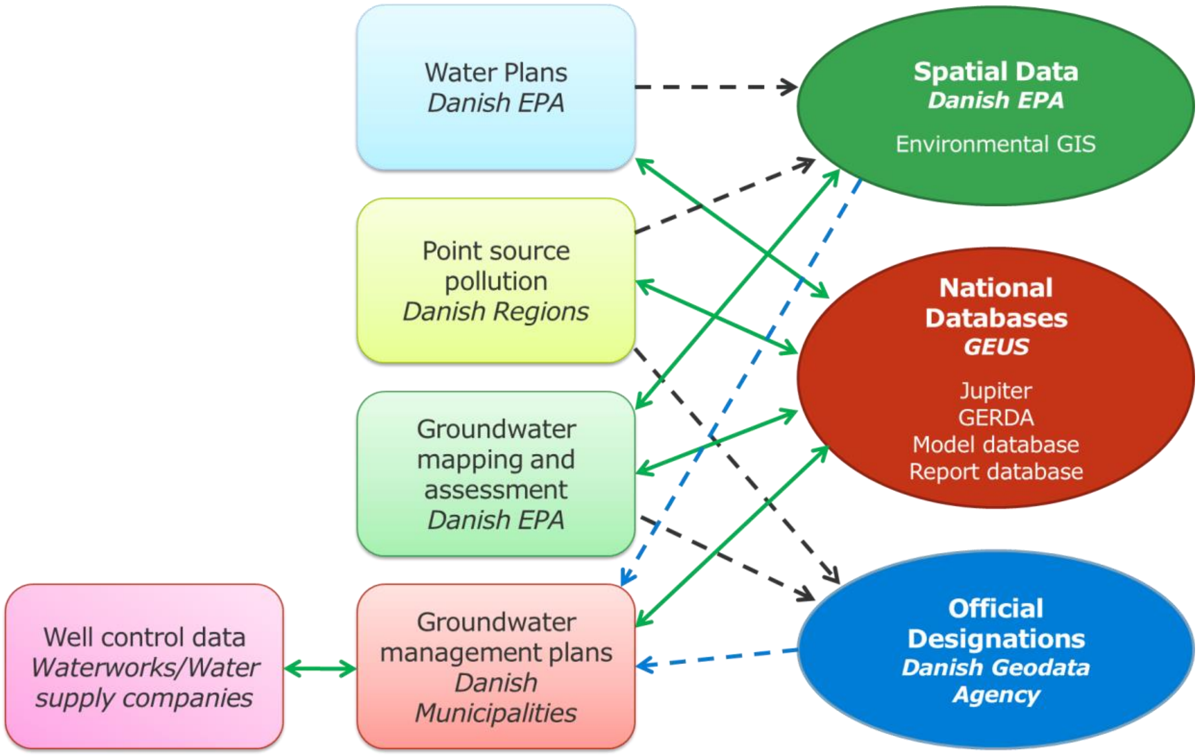

Figure 12 Diagram illustrating the data flow between the different groundwater mapping, assessment and protection programs and the different databases in Denmark. The dashed lines show one way relationship, where black dashed lines show where data are provided and blue dashed lines show where data is used. The solid green double arrows show where data is both provided and used. See text for a full description of this interaction.

As authorised by the Danish legislative initiatives, data and information on groundwater is collected through programs run by the Danish EPA, the Regions and municipalities in Denmark as well as the waterworks and water supply companies. As illustrated in Figure 12, all the entities are both consumers and providers of the groundwater data.

Starting with the water supply companies, as part of their permits issued by the municipalities, they are required to collect data from their abstraction and monitoring wells. This includes regular water level measurements, groundwater quality, pumping amounts and results from pumping tests. They can also conduct synchronous groundwater level measurements in cooperation with other nearby waterworks, stakeholders and even the municipality. All of the data collected from the waterworks is thereafter sent for approval with the municipality, which then submits this data to the Jupiter database. The Danish Municipalities frame the activities conducted by the water works through their different groundwater management plans and often assist the waterworks in accessing and using the different data stored in the databases when determining groundwater protection, abstraction strategy or location of new wells. However, the waterworks can, and often do, access these data and models directly from the databases.

For the development of the Water Plans, the Danish EPA, supported by the Geological Survey of Denmark and Greenland (GEUS) use the data in the national databases, particularly Jupiter, in the development of their national water resource model (GEUS, 2022). Particularly the water levels, pumping amounts and water quality collected by the waterworks and municipalities, provides critical data. In addition, they use geological and hydrological data collected and submitted though the groundwater mapping and assessment program as well. The results of the model work are made available through the Environmental GIS platform and the models and any extra data collected is made available through the national databases.

The Danish Regions, which work on the study and remediation of the point source pollution, rely on data from the national databases and the Environmental GIS. This is both for the prioritisation of their activities and the assessment of the threat to the groundwater resources. The data collected is thereafter made available in the different databases, as well as the status of the different pollution sites in Environmental GIS. The data collected includes new monitoring wells, water level measurements, water quality measurements and geophysical studies.

The Groundwater Mapping and Assessment Program, run by the Danish EPA, is both a significant consumer and producer of the data in the different databases. Their use of data includes all types of available data, collected by the different programs and also from earlier groundwater mapping and assessment activities. When the groundwater mapping is completed, they make all data available, including all geophysical data collected, hydrological data, groundwater quality, hydrostratigraphic models and groundwater models and simulation results. In addition, the groundwater vulnerability designations are also made available.

The Danish Municipalities are primarily a consumer of the data. The data from the above-mentioned programs provide the foundation for the development of their different groundwater management plans as well as their permitting procedures. As described before, they do also provide data to the national databases, but this data primarily comes from the waterworks, which the municipalities approve and submit the data to the different databases.

2.4 Supporting infrastructure

A supporting infrastructure was developed to assist with the national groundwater mapping and assessment activities as outlined by the Danish legislation. The groundwater mapping and assessment activities could be accomplished without the supporting infrastructure; however, it would not have been possible to carry out the activities to the detail or consistency with which it is done today. The supporting infrastructure comes in four forms:

- Establishment of national programs dedicated to groundwater mapping and assessment activities,
- development of guidelines,
- establishment of databases, and
- the development of specialised tools.

One of the most critical infrastructure developments is the establishment of programs with resources and personnel dedicated to the task of groundwater mapping and assessment. This includes Danish Groundwater Mapping and Assessment and the Water Plans (EU Water Framework) run by the Danish EPA, and the Danish Regions looking at point source pollution. Thus, the establishment of these programs provided the framework for dedicated resources and staff specific for groundwater mapping and assessment; something which may not have otherwise occurred at the same scale.

In order to support the groundwater mapping and assessment efforts, a number of technical guidelines were developed. Early on in the program, each county responsible for the mapping activities was conducting the mapping efforts individually. Here, it was realised that it would be beneficial to have a number of technical guidelines that could provide an outline of what analysis could be done and recommendations for the methods that could be used in order to assure that the mapping and assessment activities maintain a high quality. Utilising funding from the groundwater mapping and assessment program, a number of technical guidelines were developed. These include:

- Soil sampling and establishing groundwater wells,
- Geological and hydrostratigraphic modelling,
- Water level measurements and groundwater potential maps,
- Groundwater chemistry analysis,
- Hydrological modelling and calculating wellfield catchment areas
- Determining groundwater vulnerability to nitrate.

These guidelines are available on the Danish EPA's website (Danish EPA, 2022b)

An integral part of the infrastructure for groundwater mapping and assessment are the different databases that have been established (GEUS, 2022). These databases include:

- Jupiter database, which stores all borehole related data, including location, ownership, use, construction, geology (well completion reports), water level measurements, and water quality measurements as well as information on waterworks, including permits, abstraction and water quality delivered to the consumer.
- GERDA database, which holds data from geophysical surveys and borehole logs.
- Model database, which contains 3D geological and hydrostratigraphic models and groundwater models.
- Report database, which contains all reports for groundwater studies completed in connection with groundwater mapping and assessment, as well as many other reports completed from other projects.
- Environmental GIS database, containing a large amount of the spatial data and results from groundwater mapping and assessment as well as data on point source pollution collected by the Danish Regions.

These databases provide an integral storage of all publicly collected data, and some privately collected data, that is open for all to use. This has created a platform where information can easily be shared and everyone is working with the same data pool for their evaluations. As illustrated on Figure 12, all the different programs utilise the data stored in these databases.

During the course of the groundwater mapping and assessment program, funds have been made available to support the development of a number of tools that provide assistance in the mapping and assessment process. These tools have been in the form of support in the development of aerial electromagnetic surveys (SkyTEM) allowing for the rapid collection of resistivity data over large areas as well as the development of software for processing of geophysical data and geological modelling.

3. SOUTH AFRICAN GROUNDWATER ASSESSMENT AND MAPPING APPROACH

3.1 Background

Nearly 77% of South Africa's water supply is based upon surface water. Estimates of groundwater use in South Africa suggest about 15% of the total volume of water used in the country is groundwater. Historically, groundwater has always been a standalone or site-specific resource and never as regional bulk-water supply. Because of the increasing socio-economic pressures on urban water resources, groundwater is increasingly being considered as an alternative resource for urban settlements. The National Department of Water and Sanitation has the main responsibility to take care and protect all water resources. Groundwater was a private entity and became publicly owned after the promulgation of the National Water Act 36 of 1998 (NWA).

Traditionally, the water supply has been focused on a treatment process consisting of filtration and chlorination. Other treatment methods such as reverse osmosis, active carbon, advanced filtration and ozone are also used where unsuitable source water quality and pollution of water resources has been identified. Surface water and groundwater which is used for water supply is tested to determine if the quality of the water is suitable for drinking water and domestic use.

Full integration of groundwater into water resources management cannot be seen as complete yet. The first edition of the National Water Resource Strategy (NWRS) from 2004 did not see groundwater as a separate resource requiring special focus and, where necessary, separate strategic plans. The national groundwater mapping program (GRAI (1997-2000) and GRAII, developed in 2002 to 2004) produced high quality groundwater information that could be used in the management of the resource. It allowed for the recognition of groundwater as part of water resources and national water resources planning. The National Groundwater Strategy was developed into a final draft in 2016. This strategy is required to let the full potential of groundwater towards water security in South Africa unfold, to establish a framework within which stakeholders at all levels become part of groundwater governance and to initiate a long-term process of rolling out sustainable groundwater utilisation.

The National Department of Water and Sanitation (DWS) has currently a roll-out plan for the National Groundwater Strategy of 2016. After the roll-out, planning will be initiated for the national groundwater mapping program for which the National Department of Water and Sanitation is responsible.

Groundwater protection plans in response to current and future water supply threats are mainly developed on national and regional levels. Water safety plans are developed on municipal level.
The threat to future water supplies is the destruction of natural ecosystems, deforestation, surface water and groundwater depletion, land degradation and pollution, for example by anthropogenic pollution sources, chemical and agricultural waste. Environmental damage contributes to an increase in natural disasters, climate changes and water attenuation. Increased pressure is placed on groundwater resources due to over-abstraction of groundwater resources within the agricultural, industrial and municipal sectors. The decanting of old mine works, unknown hazardous waste storages, poorly sited cemeteries, landfill sites and dysfunctional wastewater treatment works are among threats to groundwater pollution.

Municipalities can apply to access bulk water infrastructure grants for funding surface water and groundwater infrastructure and maintaining it. Raw water levies and water resources management charges payable to DWS by registered, authorised and licensed water users and other sources such as taxes, are used by the Catchment Management Agency (CMA) or Proto-CMA to manage the all the water resource within the catchment. Households do pay municipalities for the volume of water used which also includes levies, as supplied to them by municipalities and or water service providers. However, domestic water users are not paying when groundwater is abstracted from a borehole or well that is situated on the water user’s property, except for levies which some municipalities charge on those properties for boreholes or wells. Poor communities receive a certain volume of water for free (free basic water – FBW) before any payment is required to municipalities.

3.2 The South African Setting

3.2.1 South African legislation

This section provides a brief description of the relevant Acts and or strategies governing the administration of the surface and groundwater resources in South Africa.

The second National Water Resource Strategy (NWRS II) of 2013 is an expansion of the National Water Act of 1998 (Act 36 of 1998) (NWA) and provides a framework for the protection, use, development, conservation, management and control of water resources. It also provides the framework within which water will be managed at regional or catchment level, in defined water management areas. The National Water Resource Strategy is binding on all authorities and institutions exercising powers or performing duties under the NWA.

The ultimate goal of the National Groundwater Strategy (NGS) of 2016 is to ensure sustainable, accessible and cost- effective supplies for human survival and socio-economic development, while maintaining the environmental services that groundwater is supporting, in an integrated development approach. The development of effective approaches requires a long-term process through which viable national, regional and local systems can evolve. Including a long-term process of rolling out sustainable groundwater utilisation within integrated water resources management.

Before each National Water Resource Strategy versions of 2004 and 2013 a Groundwater Strategy was develop as input into the NWRS providing detailed strategic action. The National Groundwater Strategy of 2016 will thus be an input to the current NWRS III that is being developed.

The South African Water Related Laws were compiled to secure the protection, use, development, conservation and managed in a sustainable and equitable manner. There are no specific laws for groundwater mapping; however, the National Groundwater Strategy of 2016 does mention that the roll-out planning will be initiated for the national groundwater mapping program at a later stage.

The DWS designate Water Management Areas (WMA). Within these water management areas there are quaternary drainage areas. Quaternary drainage regions are hydrological units that are hierarchically nested from the primary drainage basin, through to secondary, tertiary and quaternary level. The 1875 quaternary drainage regions are on average 650 km^2 in size (48 to 18096 km^2). A groundwater reserve is determined for each quaternary drainage region for groundwater allocation purposes. The delineation of these quaternary draining regions was done in according with surface water catchments. Aquifers do not necessarily follow surface water boundaries and manmade boundaries.

The National Groundwater Strategy of 2016 proposes the following stakeholder participation and collaboration:

- Aquifer management **–** joint management of shared aquifer resources by stakeholder organised in appropriate local management bodies within available plans, regulations, and guidelines.
- Action by municipalities – a professional groundwater supply service and source protection.
- Action from utilities **-** source protection, wastewater management.
- Farmers and larger agricultural ventures – institutionalised good practices.
- Mines / Energy producers / Industries – institutionalised good practices.
- Civil Society – raising public awareness, taking community initiatives and acting as watchdog.
- Media – Unique communication role in society; create public discussion.

As governed by the South African legislation, the different institutional arrangements for water are shown in Figure 13. The different actors and their roles are describing in the section below.

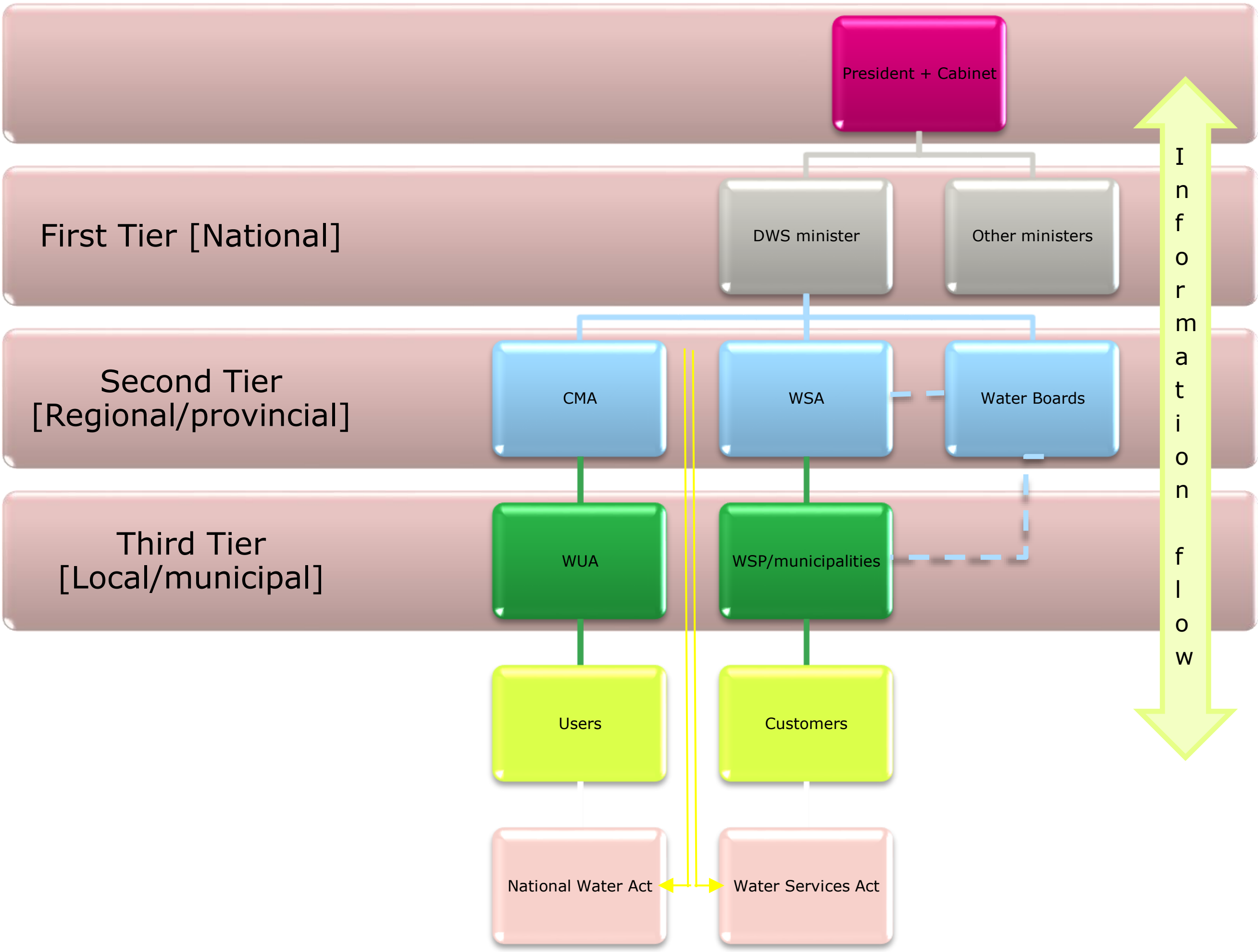

Figure 13 Responsibilities for groundwater protection on the national, regional and local level, adapted from (Kelbe and Rawlins, 2004).

3.2.2 Water supply and distribution

Water is a shared resource that is part of a continuous cycle and thus a common good that belongs to all. The minister at the head of the Department of Water and Sanitation is the custodian of water resources in South Africa, managing the resource on behalf of the people of the country. It is managed by the Department of Water and Sanitation on the day-to-day functions. Allocations are made through different forms of authorisation:

1. Schedule 1 use covers reasonable domestic use, watering of a garden and water for animals not in a feedlot.
2. Existing Lawful Use is linked to historical water use that must have been exercised before a certain date linked to the transition to the NWA.
3. General Authorisation is awarded where the impact of the water use is small enough that it does not require a full licence.

4. Water Use Licence is a water use that has a significant impact and comes with certain requirements.

DWS is the bulk raw water supplier to a large number of municipalities, agriculture, certain industries and mines. Where the Catchment Management Agencies (CMAs) are established, they are responsible for performing some of the functions as an agent of DWS, such as the water use authorisation and the collection of the raw water tariffs. DWS provides the bulk raw water out of dams and other surface water systems to the municipalities and other water users. The raw water tariffs are used to fund the work of the CMAs (and in the absence of a CMA – the branch in DWS that is responsible for managing the Water Management Area (WMA), known as the Institutional Establishment or proto-CMA), who is responsible for the management of the bulk schemes in conjunction with DWS. Proto-CMAs were established in each of the regional/provincial offices (where CMAs have not yet been established) to ring-fence the staff and functions that would later be transferred to CMAs when they are established. The raw water tariff includes groundwater, as the responsibility for the management of groundwater resources lies with the national DWS.

The Water Service Authority (WSA) is a municipality and responsible for managing the water treatment schemes, i.e. that raw water is treated to potable standards. The treatment of groundwater will depend on its natural quality. The WSA may carry out the services of a water services provider (WSP, see below) or may enter into a contract (service delivery agreement) with another water services provider.

The Water Services Provider (WSP) are the entities that physically provides water supply and sanitation services to consumers under contract to the Water Services Authority (WSA). WSA can be a municipality, Water Board, Non-Government Organisation (NGO), Community-Based Organization (CBO), or a private sector company. They maintain the reticulation infrastructure, treats the raw water to potable standards at water treatment plants and distribute it to the users. The water users within municipal boundaries – domestic, commercial, and industrial – only have to pay for the costs of production, distribution and maintenance of reticulation infrastructure.

Water Boards, i.e., Umgeni Water, Rand Water and Bloem Water, are private entities that provide treated water to the municipalities. Water boards are public (regional or bulk) water services providers that provide water services to other water services institutions. They are established and regulated by DWS under the terms of the Water Services Act and also regulated by National Treasury (NT) under the terms of the Public Finance Management Act (PFMA). They may supply water to more than one municipality. The municipalities need to pay for the services provided. Where Local Municipalities act as both WSA and WSP that process is simpler. Responsibilities of the WSA and WSP overlap depending on the local structure, i.e. where the local municipality fulfils both functions.

Groundwater management has not been delegated to local level of government at the same level as surface water, but is the responsibility of DWS and the CMA. Municipalities can only manage groundwater within the constraints of their authorisation. The Catchment Management Agencies (CMAs) are responsible for the water use authorisations. During the authorisation process, the CMA/proto-CMA considers water quality required, the amount asked for in respect to groundwater recharge (sustainable use), impacts on groundwater dependent ecosystems, and impacts on existing groundwater abstraction.

The drinking water supply based on surface water is based on a very centralised structure that is managed through the different levels of water government. Each municipality or water service provider has its own distribution area, where it has the responsibility to supply water to all residents who want to connect to the distribution system. Groundwater supply systems are managed by the municipalities (Local or District Municipalities) or the water boards, who has to comply with licence conditions and report to DWS.

The oversight for ensuring that the quality of drinking water supplied to customers by the municipalities are maintained and that they are meeting the terms in their water authorisations, falls with the CMAs and ultimately DWS. They also have to manage the quality of the source water. The responsibility of ensuring that the drinking water quality demands are met are the responsibility of the municipality or Water Board. All water use licence holders, which includes farmers, industries, municipalities and water boards, are required to report how much water they have abstracted once a year. In addition, they are required to measure water levels in their wells and take water quality samples directly from the water wells. The time interval of these measurements varies dependent upon the requirements of their Water Use Licence. All of the collected measurements are sent by the municipalities to the CMA/proto-CMA and DWS, who enter it into the national groundwater database.
There are some deviations to this structure, with a few examples below:

Victoria West within the Western Cape province:

- Farmer is WSP. Supply water to reservoir from private well field.

Kenhardt within the Northern Cape province:

- Incentives for groundwater from private farm for servitude and land management that is provided by the farmer.

Bloem Water within the Free State province:

- The water board took over the municipal wellfield and the operation of the well field. Additional wellfields are developed with private agreement between the water board and landowners (Private Service Provider)

Agricultural water use is managed through Water Users Associations (WUA) or Irrigation Boards (IB) that need to report to the CMAs. South Africa is in the process of transforming the long standing IBs into WUAs. The process started with the de-establishment of the IB's and followed by the establishment of the WUA. The transformation process is a long administrative and stakeholder engagement intensive process. Very low amount of WUAs are already establish although many IBs were de-establish already

3.2.3 Geological and hydrological setting

The South African geological setting is very complex (Figure 14) and consists of alluvial sediments and coastal dunes systems overlying shale of the Malmesbury Group and granite intrusions of the Cape Granite Suite, quartzitic sandstone that makes up the Cape Fold belt from the Table Mountain Group – part of the Cape Supergroup, followed by the Karoo Supergroup, consisting of interbedded sandstone and shale with dolerite intrusions, basalt and granite of mountains in and around Lesotho, the igneous basement complex in Limpopo in the north of the country and the Kalahari Sands. Figure 15 provides a cross section showing the geology from George on the southern Cape coast to Johannesburg in the north.

The age of the sedimentary strata of the Main Karoo Basin stretches from the Late Carboniferous to Early Jurassic. It has a cumulative thickness of about 12 km in the southern part of the basin. Outcrops of the Karoo strata can be found over an area of approximately 700 000 km^2 – more than half of the area of South Africa (Woodford and Chevallier, 2002).

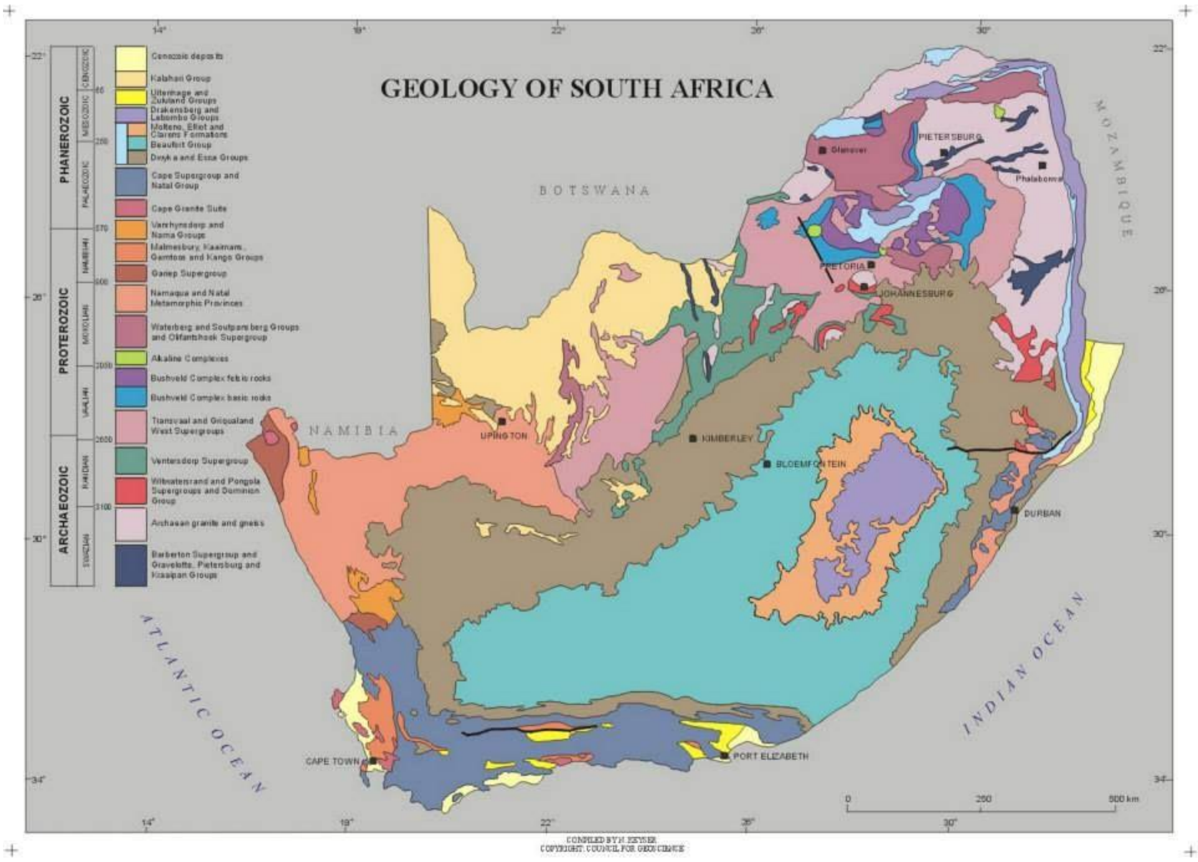

Figure 14: Simplified geological map of South Africa (CGS, 1997)

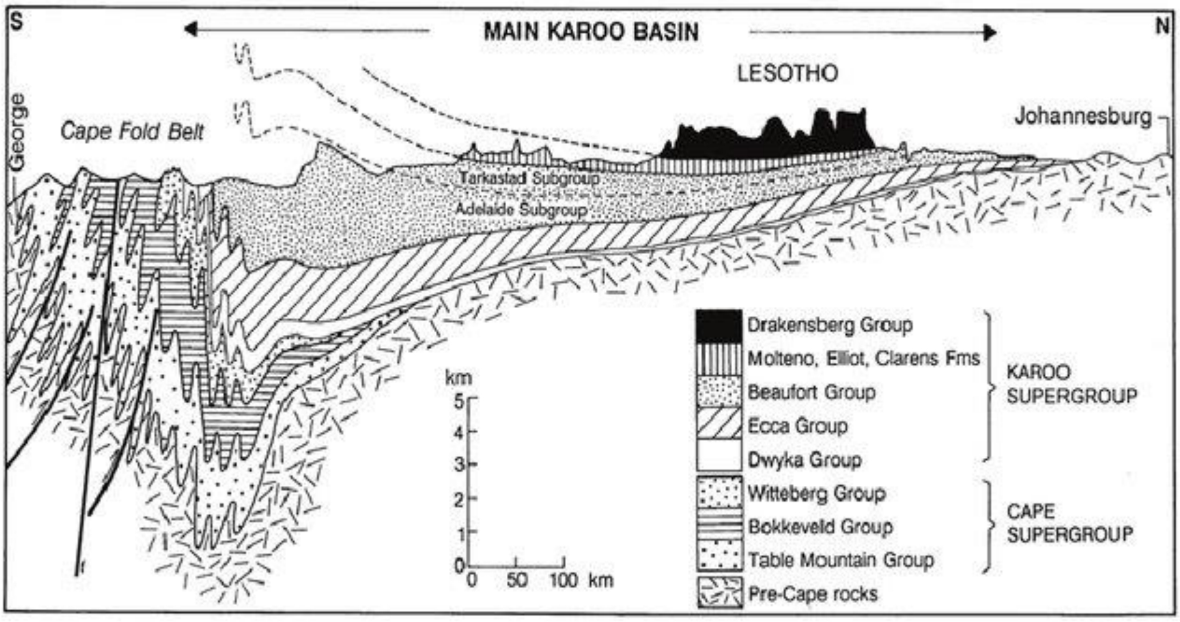

Figure 15: A simplified cross section of the main Karoo Basin from George in the south to Johannesburg in the north (Woodford and Chevallier, 2002).

About 90% of the aquifers in South Africa are hard-rock fractured aquifers, with the Karoo aquifers of sandstone, shale and mudstone making up the largest group (See Figure 16). Basement aquifers, quartzitic sandstone aquifers, karst aquifers and aquifers in igneous rocks complete the hard rock aquifers. Coastal aquifers and other porous aquifers make up the remaining 10%. They are nevertheless important as a source of groundwater for water supply purposes at a local scale. The geology determines the characteristics of the various aquifers, such as recharge potential, flow, and quality.

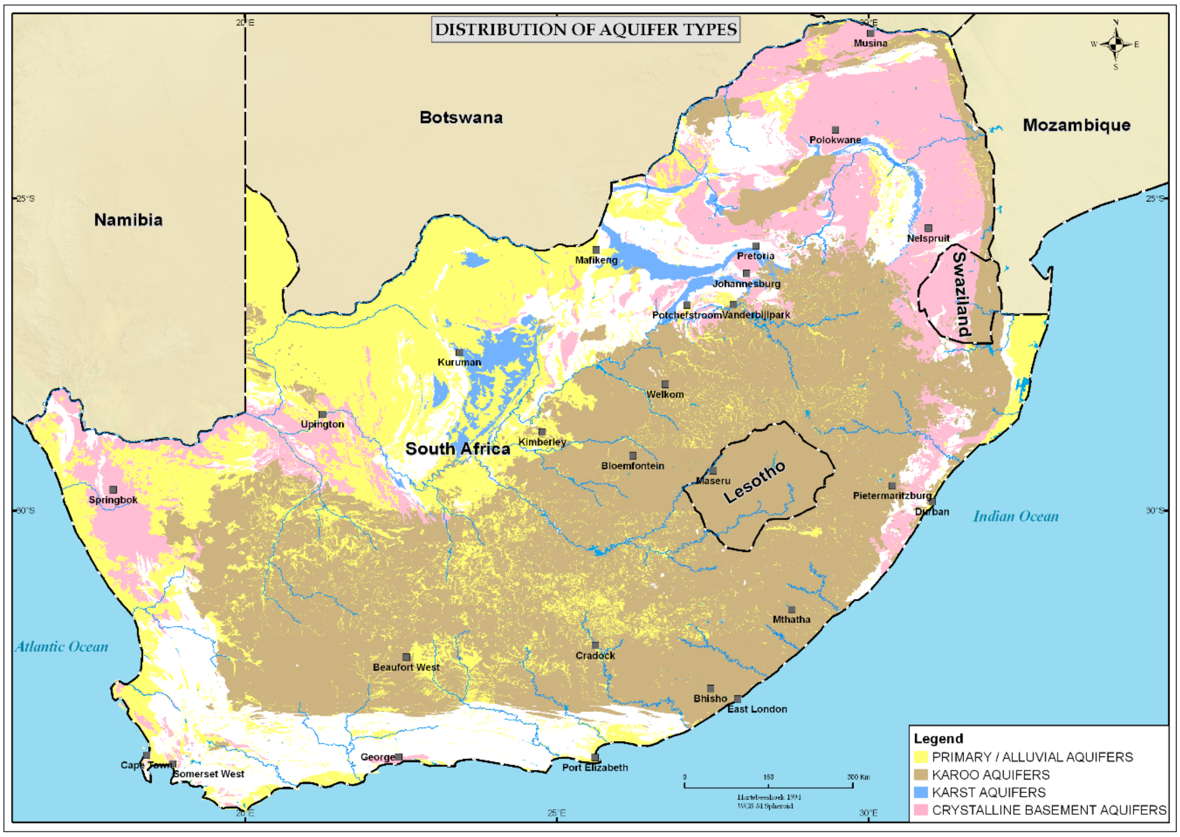

Figure 16: Distribution of aquifer types in South Africa.

Precipitation in South Africa varies from less than 100 mm/year on the northern West Coast and along the lower Orange River, to more than 1200 mm/year along the East Coast and some of the high mountains in the Western Cape and Mpumalanga (Figure 17). The mean annual precipitation of the country is far below the world average, which earns South Africa the designation of a semi-arid to arid country. The pattern of infiltration of rainfall to recharge groundwater is dependent not only on precipitation, but also on soil type, geology, land use, temperature and evapotranspiration.

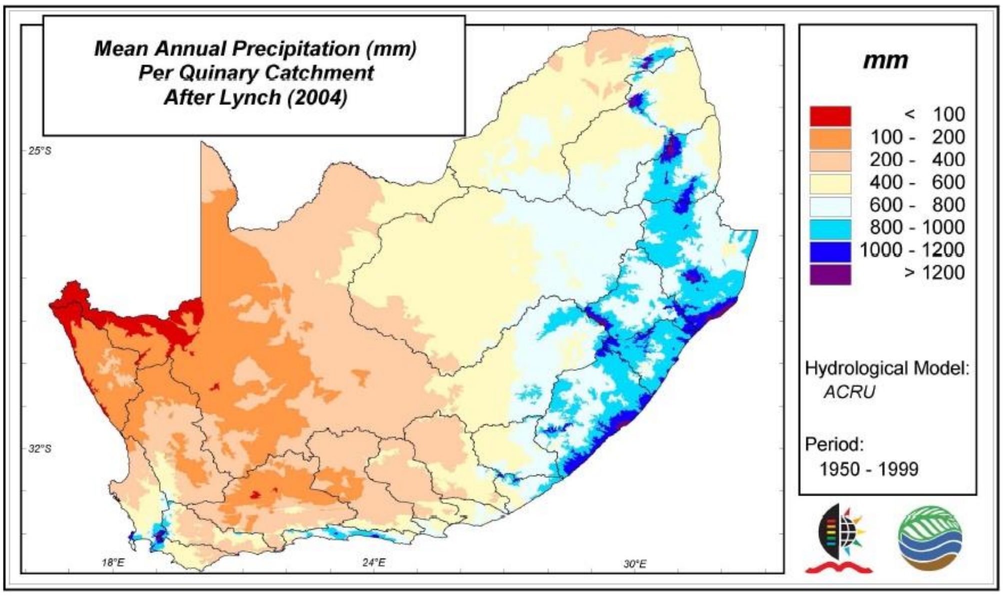

Figure 17: South Africa's Mean Annual Precipitation (MAP) (Schulze 2011).

The evaporation rate in South Africa is high (Figure 18), varying from more than 3000mm/year in the northern parts of the Kalahari to less than 1400 mm/year on the east coast, south coast and the high mountains in the Western Cape. The evaporation rate is higher than the mean annual precipitation, which has implications for water management.

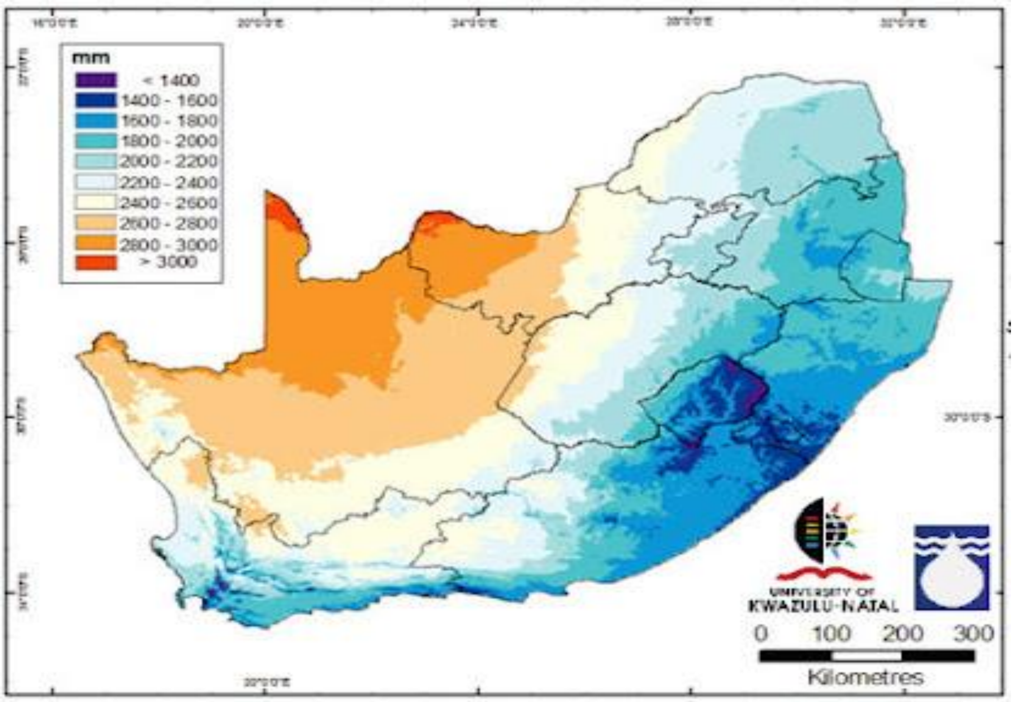

Figure 18: Map of evaporation from open-water surfaces across South Africa (mm/a) (Schulze, et al., 2008).

Recharge follows the same general pattern as the precipitation and evaporation maps, Figure 19, with higher recharge expected in the east and south of the country, and low recharge to the west and north.

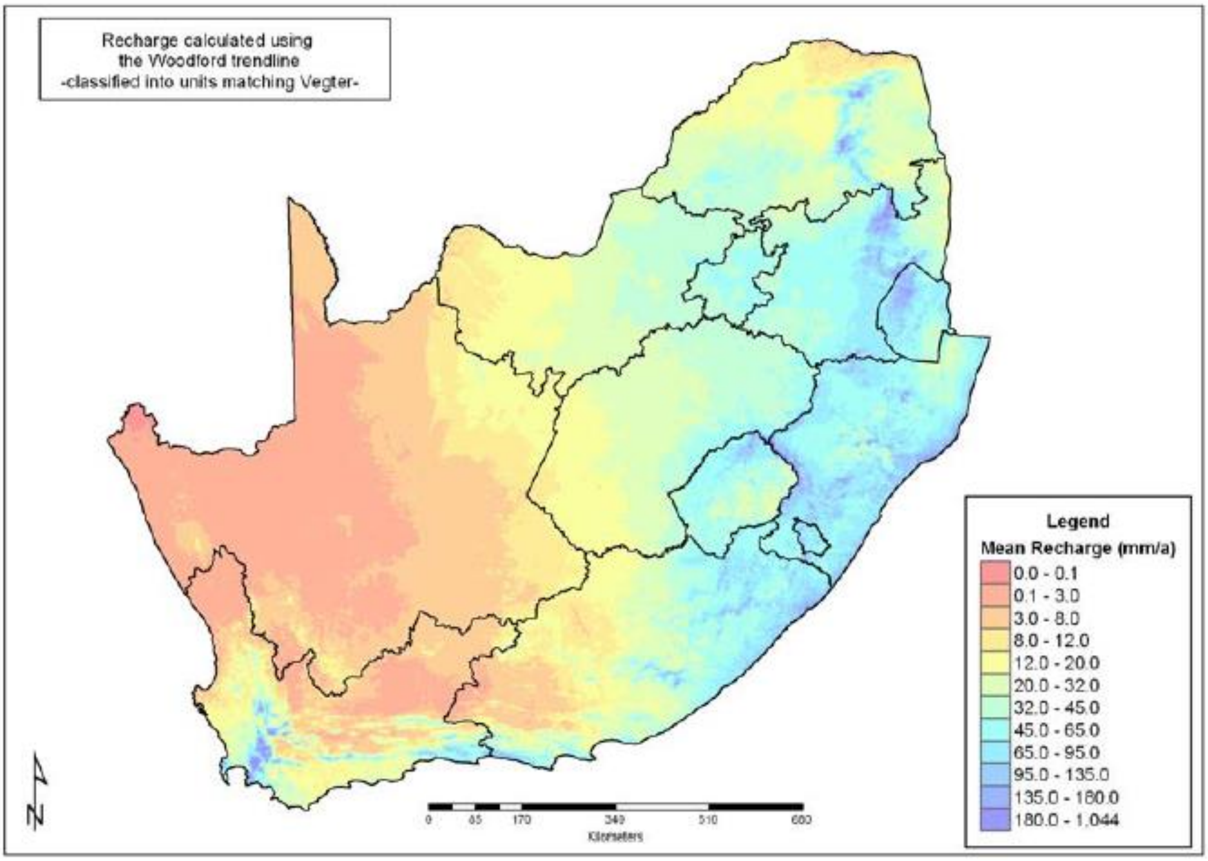

Figure 19: Groundwater recharge map of South Africa - derived from the Woodford rainfall /recharge relationship (DWA, 2005)

3.2.4 Challenges and threats

Threats to groundwater are related to both quantitative and quality aspects. Quality threats include diffuse and point-source pollution.

The most general diffuse source of pollution comes from agriculture where potential pollutants are nitrates, pesticides and herbicides. Feedlots is also a potential source of nitrates and phosphates.

Point-sources that are most often associated with urban settings includes filling stations (volatile organic compounds, i.e., hydrocarbons, BTEX; also heavy metals and chlorinated solvents), cemeteries (bacteria such as *Escherichia coli* and *Clostridium perfringens;* nitrates), landfill sites (leachate containing soluble and insoluble organic and inorganic products from physical, chemical, hydrolytic and fermentative processes), and wastewater treatment works (nitrogen and phosphates), while French drains and soak-away sanitation systems are usually a problem in rural settings.

Mining also has the potential to pollute groundwater, with contaminates linked to the geology, the ore bodies and the processing of the ore. One important example is the acid mine drainage that is a big problem in the karst aquifers especially within the Witwatersrand.

In addition to anthropogenic threats, natural water quality of groundwater may not comply with potable standards, as contamination linked to the geology may cause high levels of arsenic, fluoride, iron, manganese and nitrates. The natural occurring pollutants include the high salt content of shale, high iron and manganese concentrations associated with the Table Mountain Group aquifers, etc. High fluoride and arsenic have also been measured. Groundwater abstraction can also induce seawater intrusion into the groundwater aquifer, degrading water quality.

The extent of the pollution from natural (geogenic) sources and human activities are often not known, as groundwater monitoring is limited.

Groundwater quantity is under threat both due to limited recharge and due to the complexity of the groundwater systems where approximately 90% of the surface area of South African groundwater can be found in secondary openings in hard rock. The yields associated to the different aquifer systems are often not very high. High yields are mostly associated with the coastal aquifers, highly fractured aquifer (such as the Table Mountain Group) and karst aquifers. Poor management practices can lead to over-abstraction and over-allocation of the resource, with all its potential impact such as a reduction of baseflow to rivers, the collapse of the aquifer and subsidence. This is exacerbated by highly variable recharge.

Figure 20 provides an overview on registered groundwater use across South Africa according to the WARMS database. It tends to follow the same pattern as the precipitation, evaporation and recharge maps, except in the most eastern parts where high precipitation made the use of groundwater unnecessary. Agriculture is a large water consumer where irrigation is responsible for about 60% of water use in South Africa.

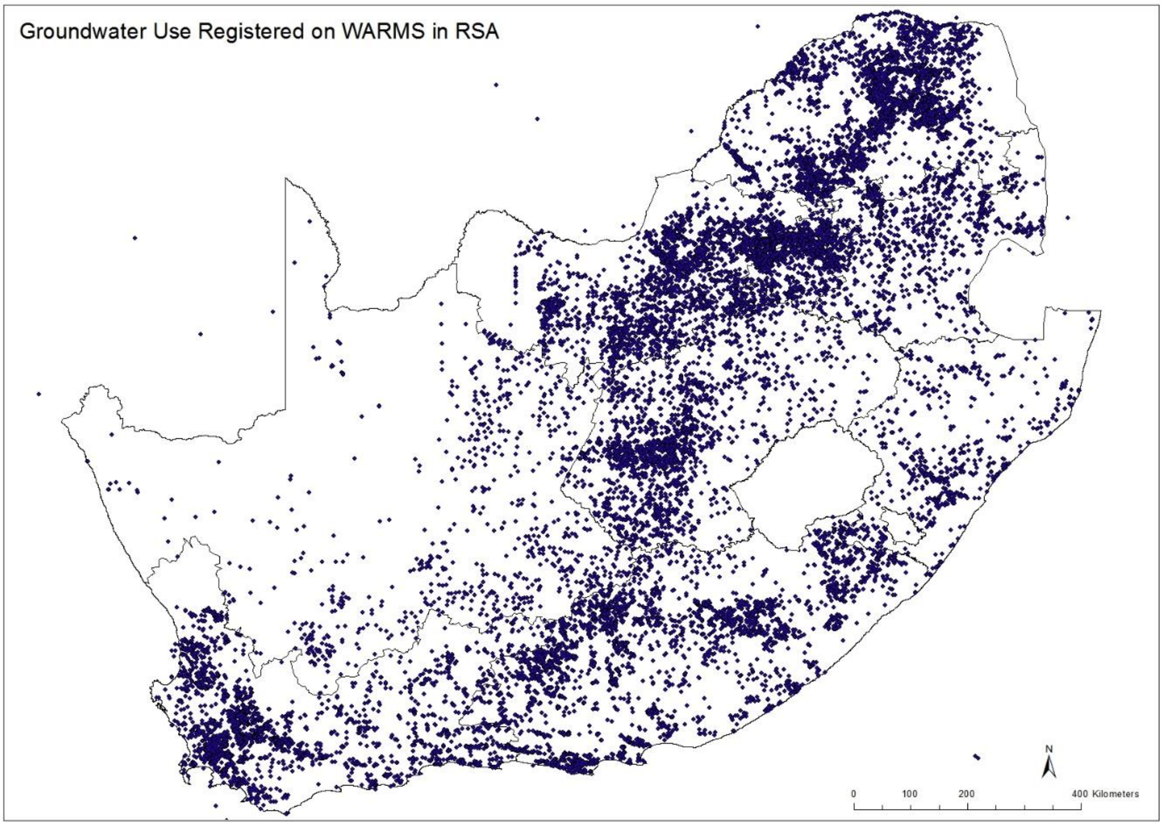

Figure 20: Indication of groundwater use based on water use registrations on the WARMS data base.

Figure 21 and Figure 22 provides a comparison between groundwater availability and registered groundwater use. In Figure 21 the comparison is done according to Water Management Area (or river catchment). Groundwater in the Berg-Olifants WMA is over-allocated according the current volumes for groundwater availability, while the Pongola-Mtamvuna WMA has almost no groundwater abstraction. Figure 22 provides the same analysis for each province, with the Gauteng Province being over-allocated, while KwaZulu-Natal has almost no groundwater abstraction. This correlates with the trend seen in Figure 20.

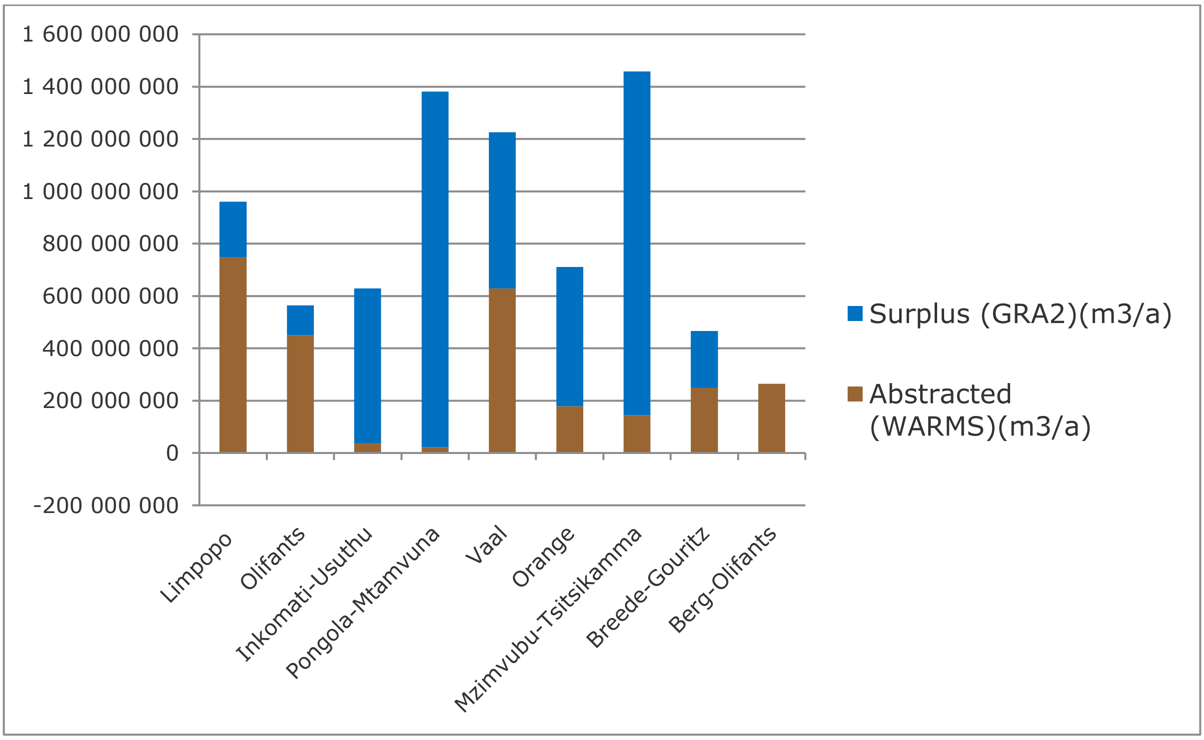

Figure 21: Groundwater availability compared to water use registered on WARMS according to Water Management Areas.

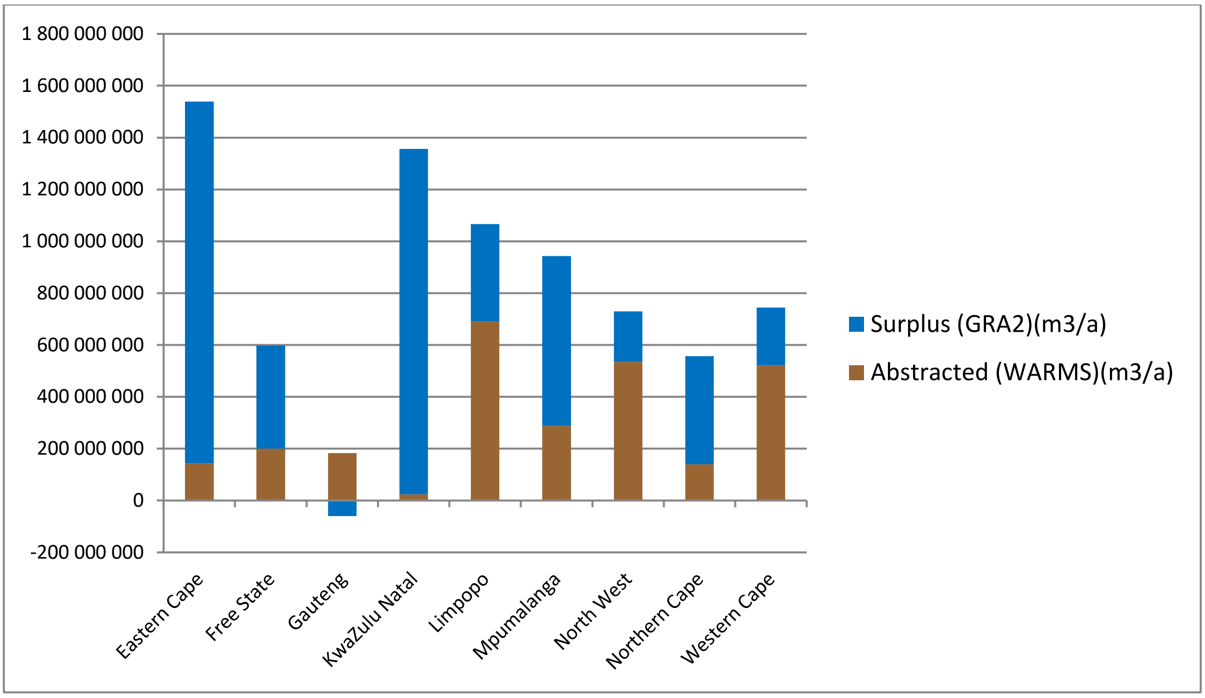

Figure 22: Groundwater availability compared to water use registered on WARMS according to provincial boundaries.

3.3 Concept and structure of groundwater mapping and assessment

3.3.1 Groundwater mapping and assessment

Groundwater mapping and assessment is done at different levels in South Africa (See Figure 23 for a brief summary), depending on the purpose of the study, e.g. site specific explorations required to establish wells/wellfields or national assessments required to attain an overall overview of the groundwater resource, its availability and quality. Additional factors controlling the studies are the size and complexity of the studies.

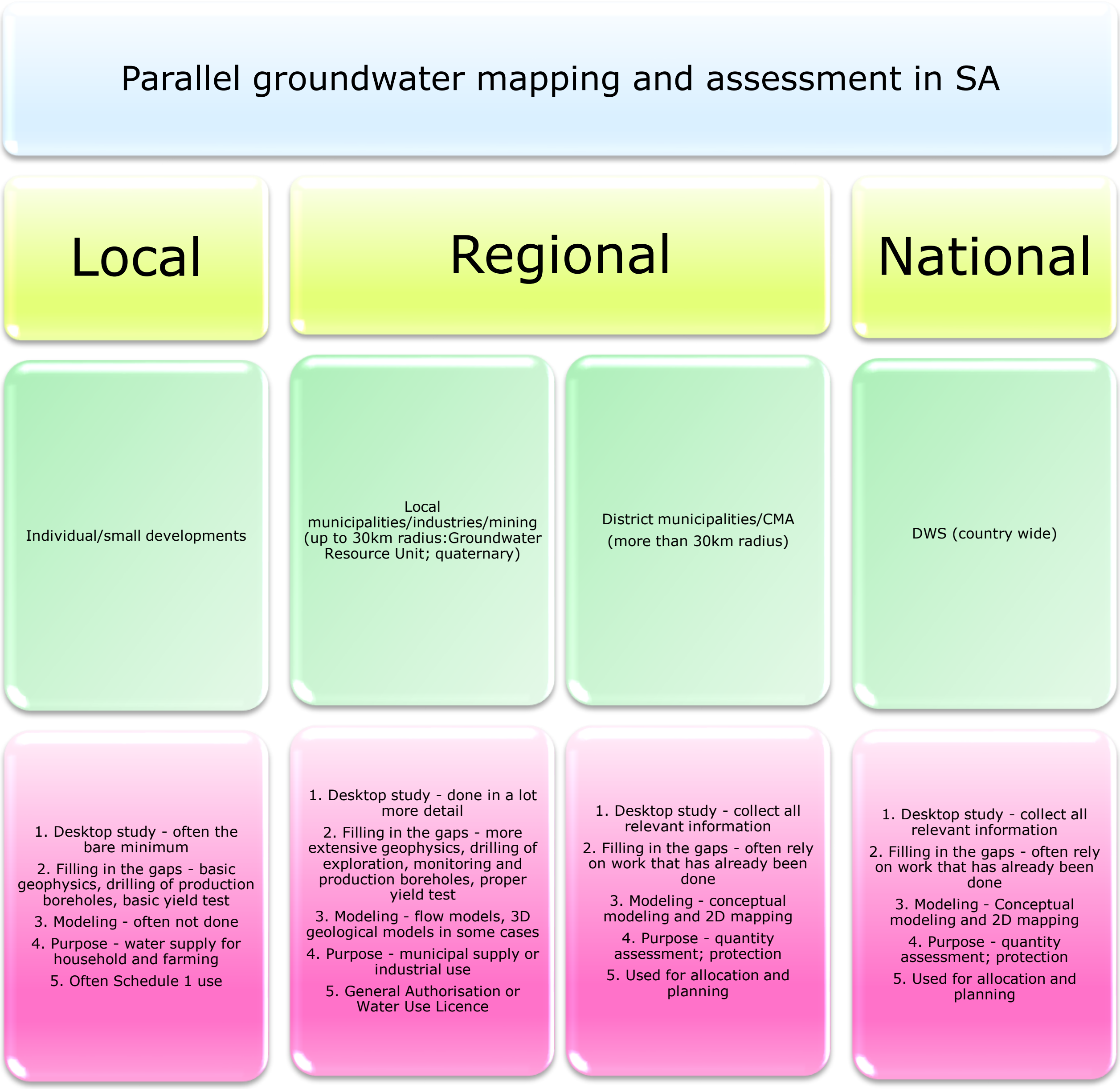

Figure 23: Parallel processes for groundwater mapping and assessment in South Africa at different levels.

3.3.1.1 Site specific assessments

Site specific groundwater assessment is done on different scales, depending on the client and the level/volume of groundwater use. Basic water supply will entail the most basic assessment with the least amount of data collected and no monitoring or management afterwards. An industrial client or municipality will lead to a more detailed assessment with greater data collection, monitoring and management afterwards. The level of the investigation usually dependent on the requirements for a license versus a GA and the willingness of client to spend additional money.

Data collection for many small-scale assessments are often limited. Clients may call in the assistance of a consultant (hydrogeologist) to assist with exploration, geophysics, etc., but this is mostly reserved for the larger clients that can afford to hire a consultant. When data are collected it is not made available for a groundwater mapping phase. This means that there is a large amount of potential valuable information that gets lost with the smaller clients.

The flow diagram in Figure 24 gives an indication of the basic approach that is followed for a groundwater assessment for the development of a bulk supply to a municipality. Smaller scale groundwater developments do not follow these steps, and data that could inform groundwater assessment and mapping at national scale are not always collected.

Early groundwater exploration work (1960s to 1990s) went through the whole process of desktop survey – geological maps, etc., hydrocensus work (collecting groundwater related data), geophysics, exploration drilling, pumping tests, developing maps – sometimes very basic, but in some cases very detailed, and in some cases a numerical groundwater model.

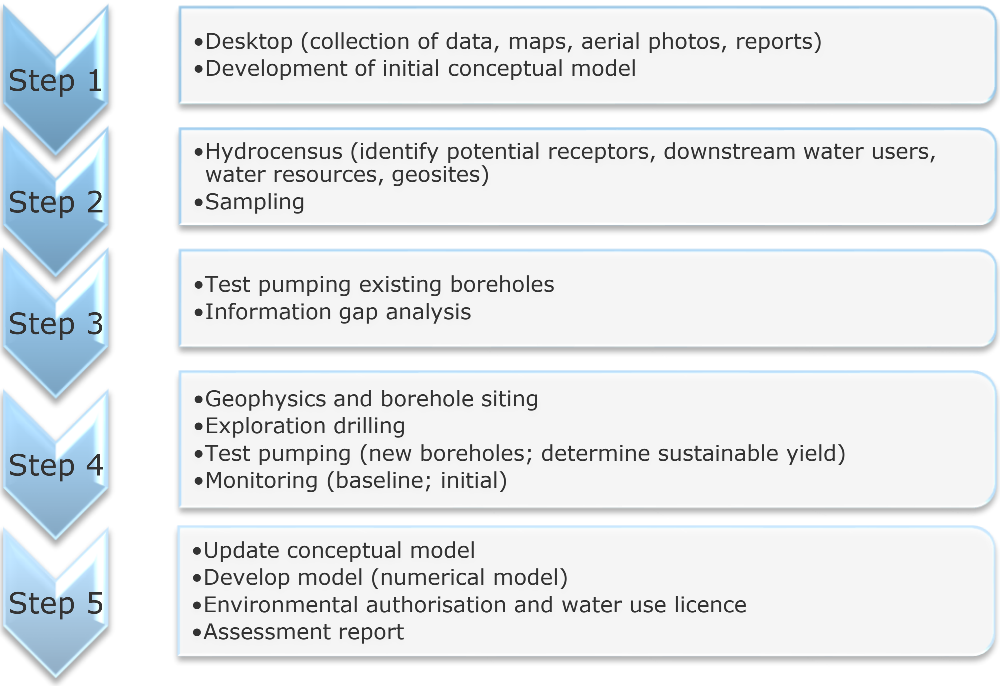

Figure 24: Flow diagram providing the steps for a groundwater assessment.

Below are the steps followed in two case studies, illustrating that the steps may vary from one case to the next.

Case study: Free State:

- Collection of existing geohydrological data;
- Perform a hydrocensus which is typically for groundwater potential and development schemes done within a 30 kilometres radius per project within the Free State;
- Interpret aerial photographs;
- Interpret aerial magnetics;
- Perform a geophysical field survey;
- Compilation of GIS maps;
- Determination of high groundwater abstraction areas;
- Recharge volume estimation; and
- Compilation of a Geohydrological Potential Report.

Case study: Vaal Gamagara Groundwater Potential and Development Scheme within the Northern Cape province:

- Detail desktop study: Collection and updating of existing geohydrological data;
- Land Owner Engagement process;
- Perform a hydrocensus: Identification and verification of water use and sampling;
- Perform high resolution airborne geophysical surveys: electromagnetic and time-domain electromagnetic surveys;
- Detail remote sensing and assessment of airborne geophysical data;
- Ground geophysical field survey: electromagnetic and gravity
- Test pumping existing boreholes;
- Drilling of exploration/test boreholes;
- Groundwater sampling on newly drilled boreholes;
- Aquifer test pumping of exploration boreholes:
- Short term test: Sustainable discharge test and 24h Constant discharge test – borehole yield capacity + aquifer sustainability
- Long term test: 72h – aquifer sustainability + aquifer hydraulic parameters for modelling
- Conceptualising of hydrogeological model;
- Numerical 3D modelling: simulate aquifers + predict long term pumping performance + test feasibility of implementing development;
- Management recommendations: production design + buffer effect; and
- Compilation of investigation report.

3.3.1.2 National assessments/compilations

The assessment of groundwater at the national scale is seen as the responsibility of the national Department of Water and Sanitation. Various efforts have been made to map groundwater and its characteristics in South Africa. This has relied heavily on the early work that was done by the Geological Survey and later the Geohydrology Directorate of the Department of Water Affairs (Vegter maps and GRAI). Work done later (GRAII) by consultants were incorporated in later mapping and quantification, but most of the data used for the development of the Hydrogeological map series were from the NGDB (now (NGA).

Groundwater Quality Map (Bond, 1949)

The first map was compiled in 1949 (See Figure 25) and provides an indication of the groundwater quality of South Africa.

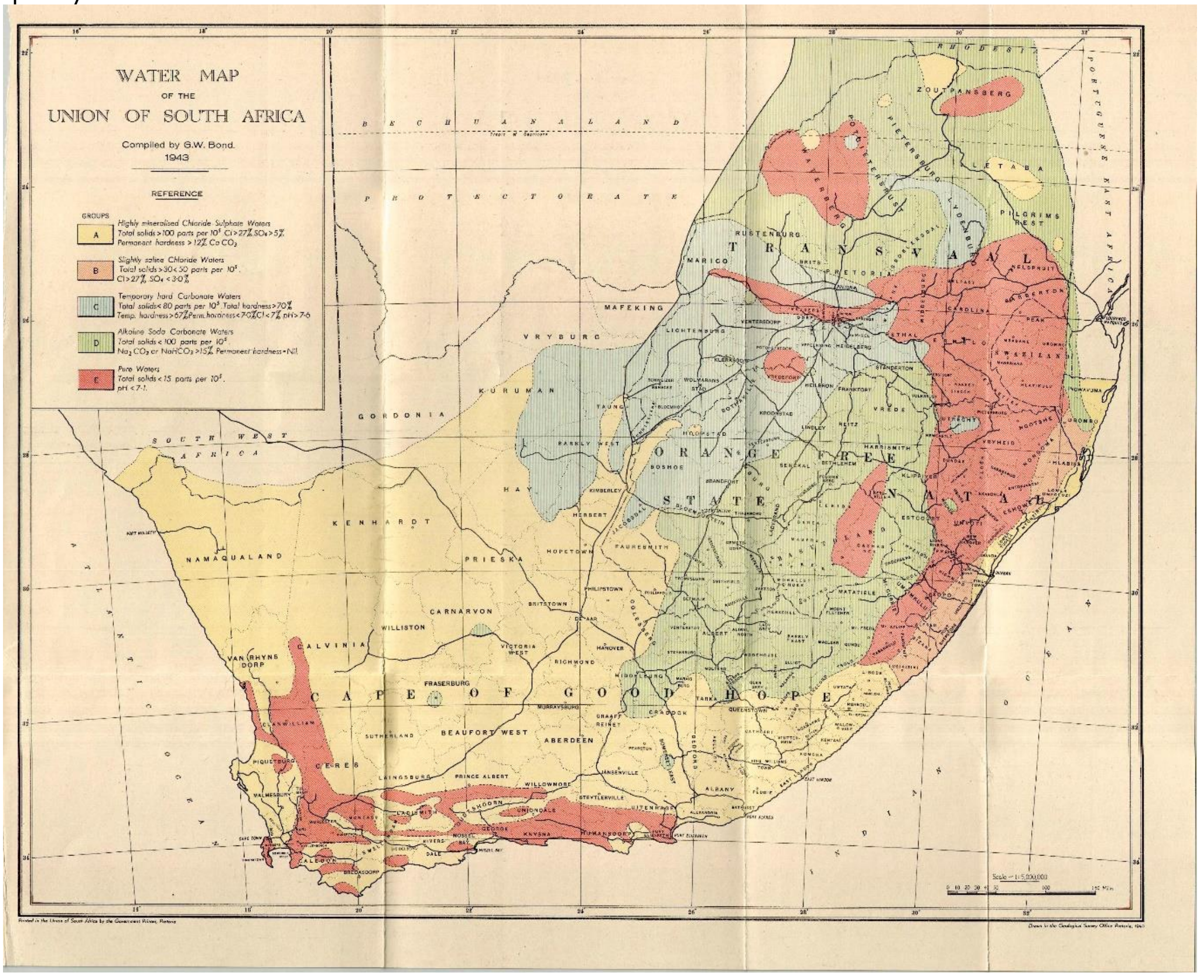

Figure 25: The first groundwater quality map produced for South Africa (Bond, 1949).

Vegter, 1995

Early national scale maps were produced as a set of two maps, containing information such as recharge (Figure 26), borehole yields, water strikes, possibility of drilling a successful borehole and other hydrogeological characteristics. It was one of the first attempts to quantify groundwater availability for South Africa. The maps are explained in two reports published by the WRC (Vegter, 1995).

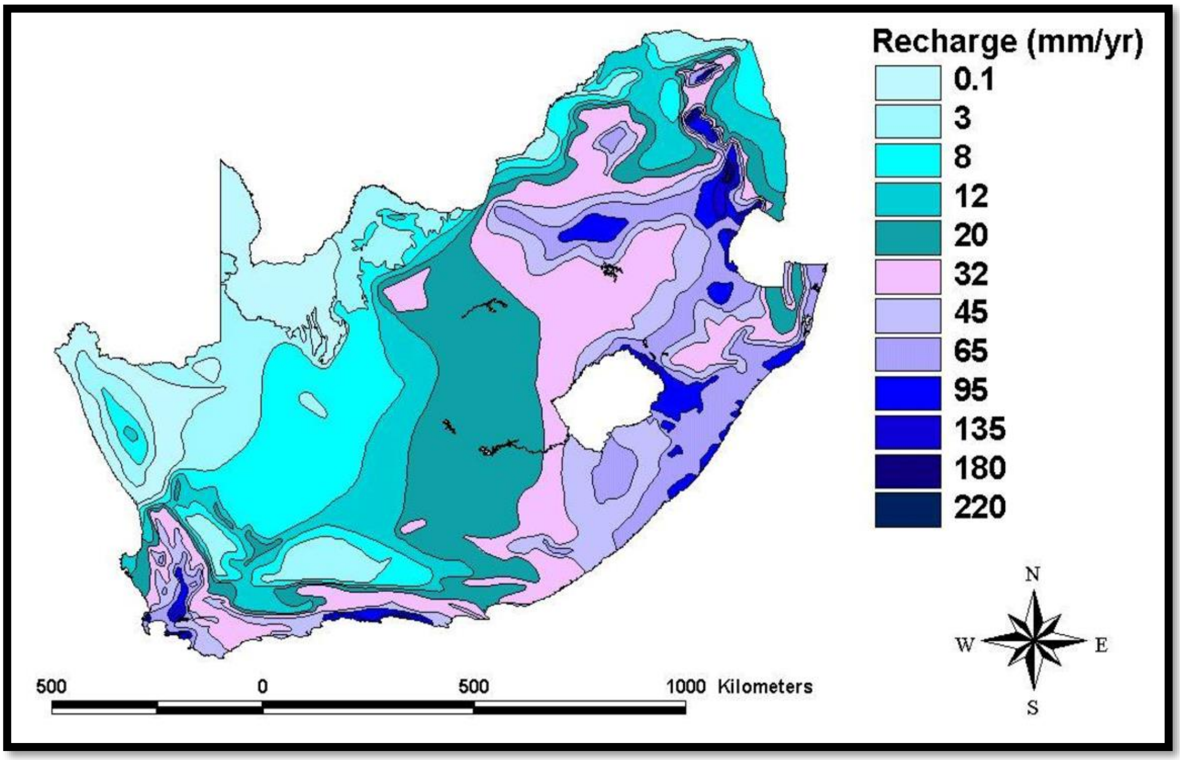

Figure 26: Groundwater recharge map (Vegter, 1995).

Harvest potential map (Baron, et al., 1996)

The Harvest Potential maps were the second attempt at quantifying the available groundwater resource. It built on the work of Vegter (1995) and used the recharge, storage and time between recharge events to estimate a national sustainable groundwater resource value. A number of maps were produced as part of the project.

GRA I (Hydrogeological Map Series and Brochures)

The Department of Water and Sanitation had during 1995-2003 provided a classification of the aquifers into four classes during the development of the 1: 500 000 Hydrogeological Maps (GRA I). These maps covering the whole of South Africa were published as a set of 21 hydrogeological maps. The accompanying explanatory brochures for most of the maps were developed.

The aquifers are classified as follows:

- Intergranular (Class A) are aquifers associated either with loose and unconsolidated formation such as sands and gravels (primary aquifer), or with rock that has weathered to the extent where its primary structure is that of loose or only partly consolidated material (secondary aquifer). Under these circumstances, water is stored in and transmitted through the intergranular voids that render the material porous and permeable.
- Fractured (Class B) describes aquifer associated with generally hard and compact rock formations in which fractures or joints occur that are capable of both storing and transmitting water in useful quantities.

- Karst (Class C) Karst describes aquifers associated with carbonate rocks (dolomite or limestone) in which groundwater is predominantly stored in and transmitted through cavities and/or fractures.
- Intergranular and Fractured (Class D) are aquifers in which the intergranular interstices serve primarily as a storage and water is transmitted mainly through the fracture-type interstices. This is a common feature for many South African aquifers.

With more than 90 % of South Africa's aquifers are classified as secondary aquifer systems (intergranular & fractured). Thus, groundwater occurrence is mainly controlled by secondary fractures systems. Therefore, understanding the geology and geological processes (faulting, folding, intrusive dyke/sills, weathering) responsible for the development of these fracture systems and how they relate the geohydrology becomes an important tool in locating groundwater resources.

The development of GRAI coincided with the development of the National Groundwater Database (NGDB), which was the predecessor of the National Groundwater Archive (NGA). This formed the basis of the 21 hydrogeological maps. Figure 26 is a typical example of the maps produced for South Africa.

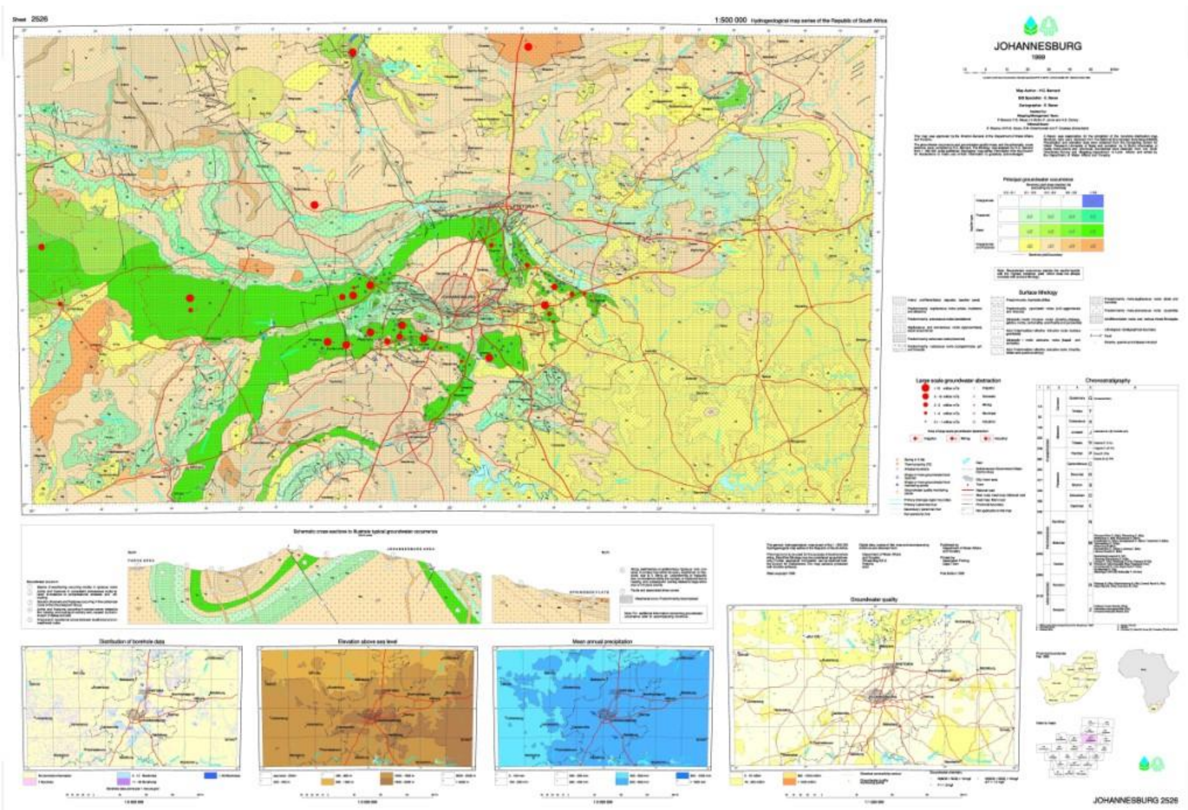

Figure 27: A typical example of the hydrogeological maps produced as part of GRA 1.

Figure 28 provides a compilation of the 1:500 000 scale hydrogeological map series. The reason for groundwater mapping to date was to provide an overview of aquifer characteristics.

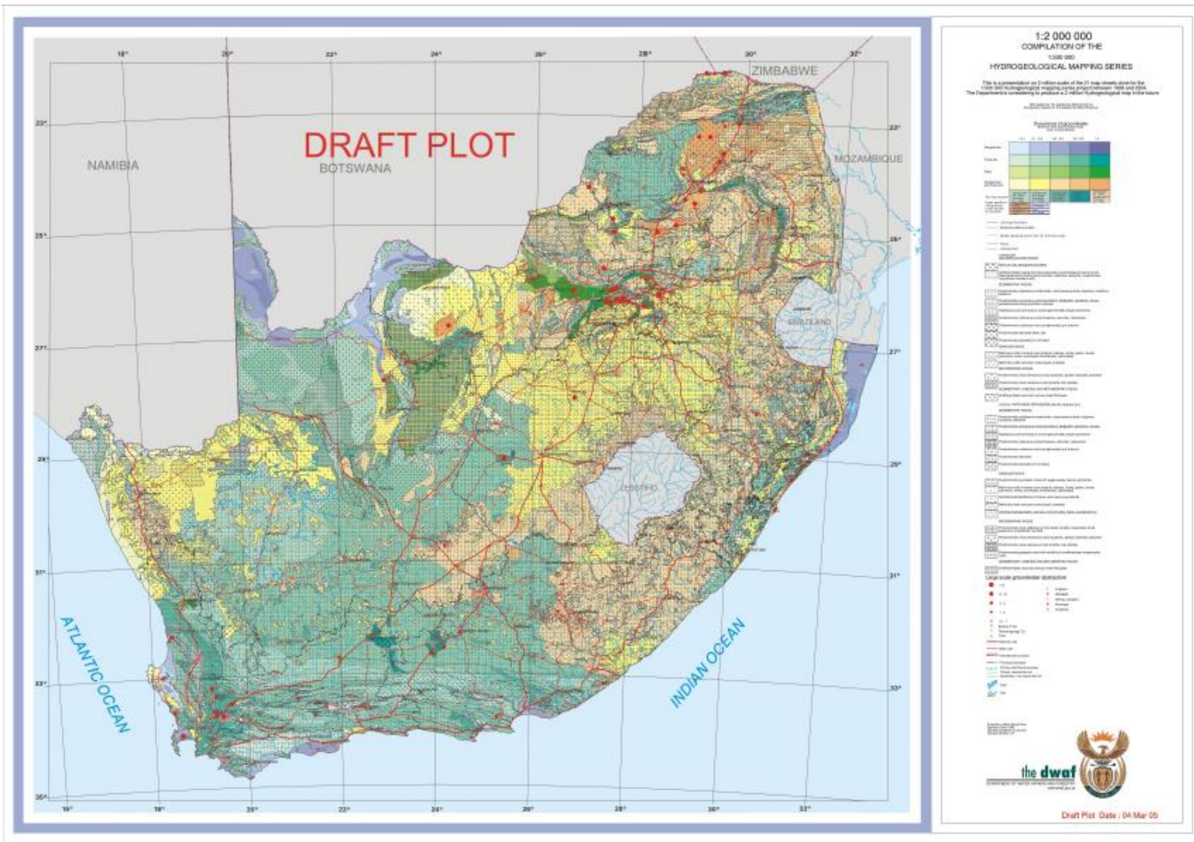

Figure 28: A 1:2 000 000 scale compilation of the 1:500 000 scale hydrogeological map series of South Africa, from GRA 1.

The following maps are an amalgamation of the 21 hydrogeological maps, portraying one parameter, with Figure 29 showing the expected borehole yield, Figure 30 the aquifer type and Figure 31 the electrical conductivity.

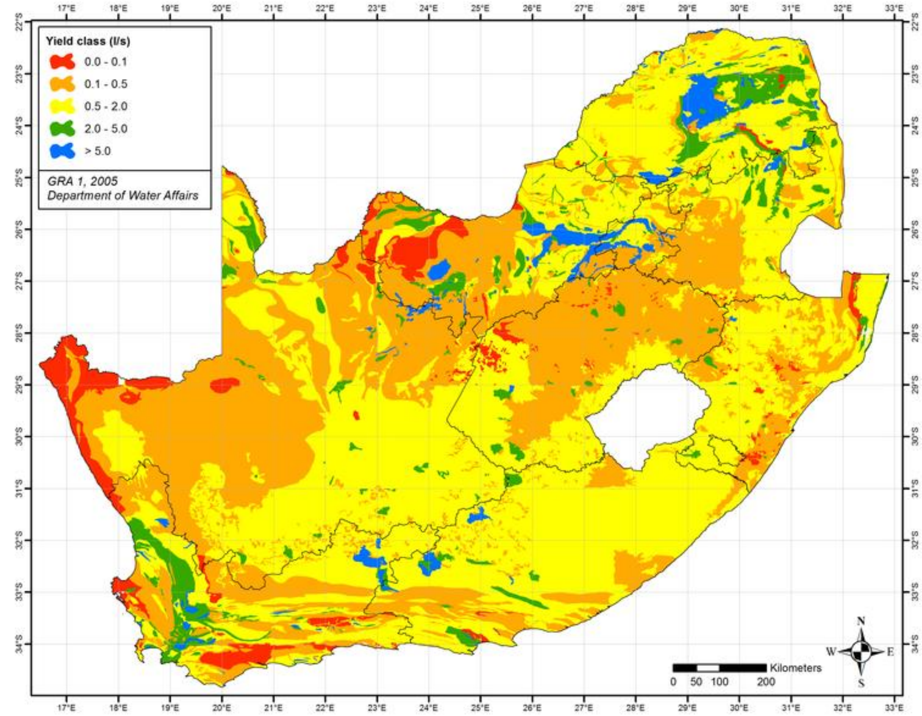

Figure 29: An amalgamation of the 1:500 000 hydrogeological map series, giving a country-wide extent of the expected borehole yield, from GRA 1.

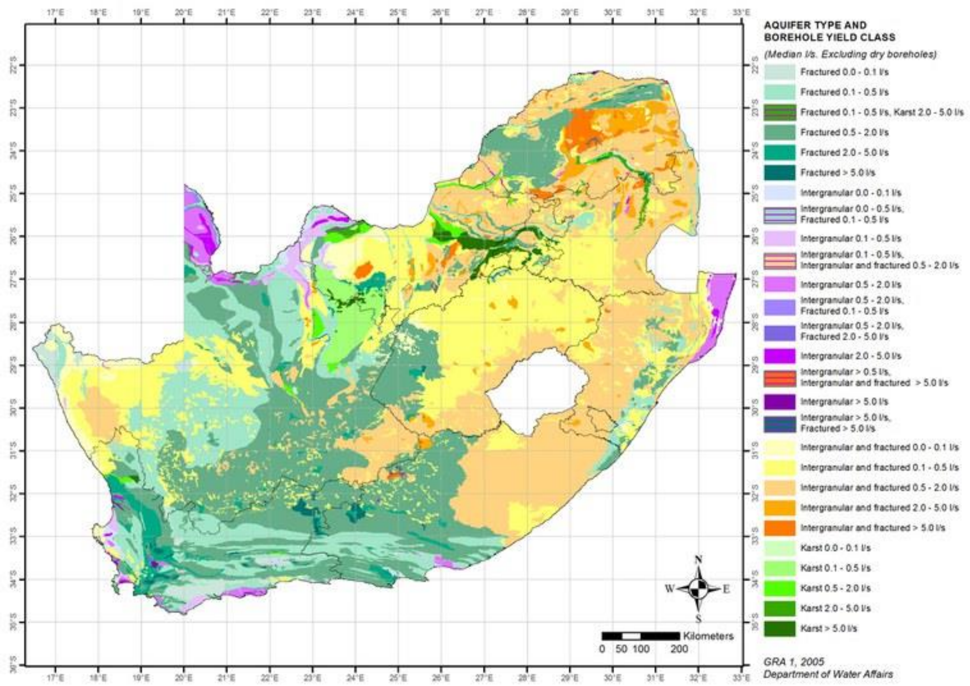

Figure 30: An amalgamation of 1:500 000 Hydrogeological Map series, giving a country-wide extent of aquifer type (groundwater classification) and expected borehole yield, from GRA 1.

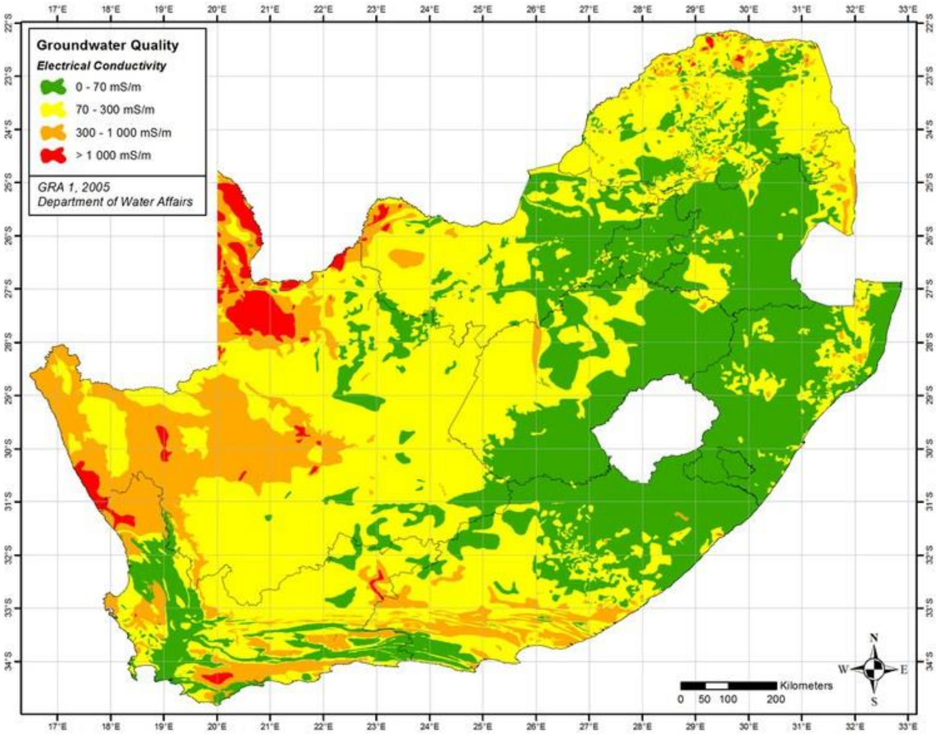

Figure 31: Amalgamation of Hydrogeological Map series, giving an interpolated country-wide extent of the Electrical Conductivity of groundwater, from GRA 1.

GRA II

In late 2003, the Department of Water and Sanitation initiated the Groundwater Phase 2 Project (GRA II) which is aimed at the quantification of the groundwater resources of South Africa on a national scale and was completed in June 2005. The project developed algorithms for the estimation of storage, recharge, baseflow and the impact of the reserve and present groundwater used. The main purpose of the was to aid in allocating groundwater use.

The primary aim of GRA II was not the production of maps, but quantification of groundwater resources. It built on the work of Vegter, Baron and GRA I, with improvements to the methodology. It determines a Utilisable Groundwater Exploitation Potential that is conservative and that can help with the allocation of groundwater through the various water use authorisations, while ensuring that there is a Reserve to supply basic human needs (25 litre per person per day) and the environmental needs. Maps were plotted with the data as can be seen in Figure 32. It is still used extensively and forms the bases of some of the software program, such as the Firm Yield Model.

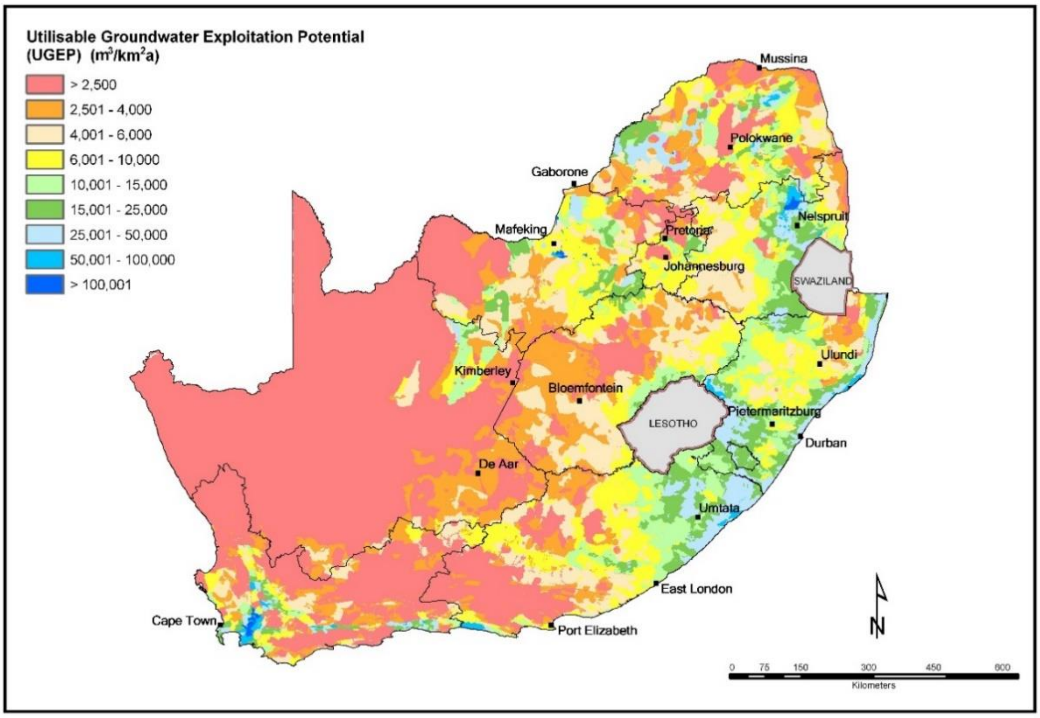

Figure 32: Map showing the Utilisable Groundwater Exploitation Potential for South Africa.

GRIP

The Groundwater Resource Information Project (GRIP) was developed with the aim of assisting in the gathering of groundwater data and to use it to improve assessment and management of groundwater resources within rural South Africa. It was initiated in Limpopo Province in 2002/2003 by continuous process of capturing and conducting field verification and investigations of the groundwater data, to confirm information where available and to obtain essential information in areas where there is not available.

GRA III

The proposed methodology continues to build on the previous work, with improved quantification of the groundwater contribution to baseflow (Allwright, 2013), and other improvements. GRA III is still in the development phase, and is thus not complete.

Groundwater Protection

A number of maps were plotted with groundwater protection in mind. This includes the Aquifer vulnerability map (Figure 33), and the Aquifer susceptibility map (Figure 34). The Strategic Water Source Areas project by the WRC were conducted to map recharge areas, important aquifers and aquifers of importance as sole supply of water to communities.

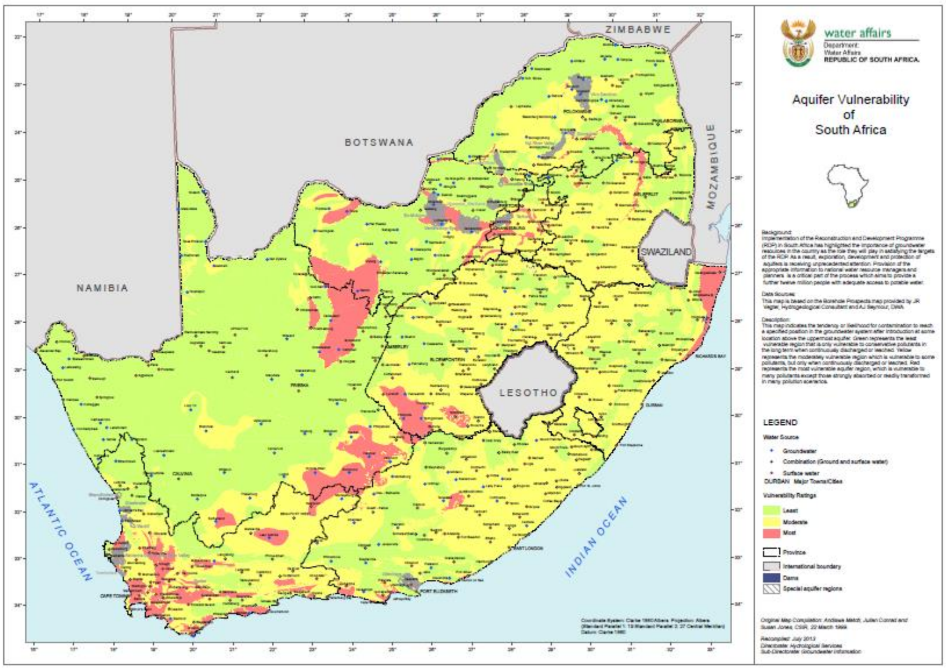

Figure 33: Aquifer vulnerability map of South Africa.

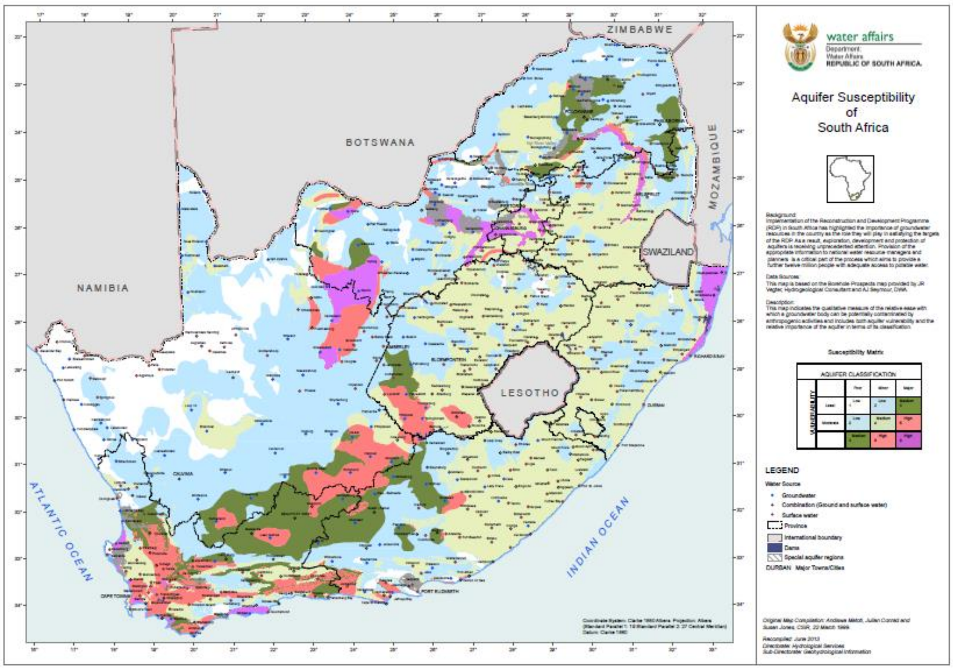

Figure 34: Aquifer Susceptibility map for South Africa.

The Strategic Water Source Areas project were completed in 2018 (See Figure 35). This project included both surface water and groundwater. It identified where water sources should receive better protection.

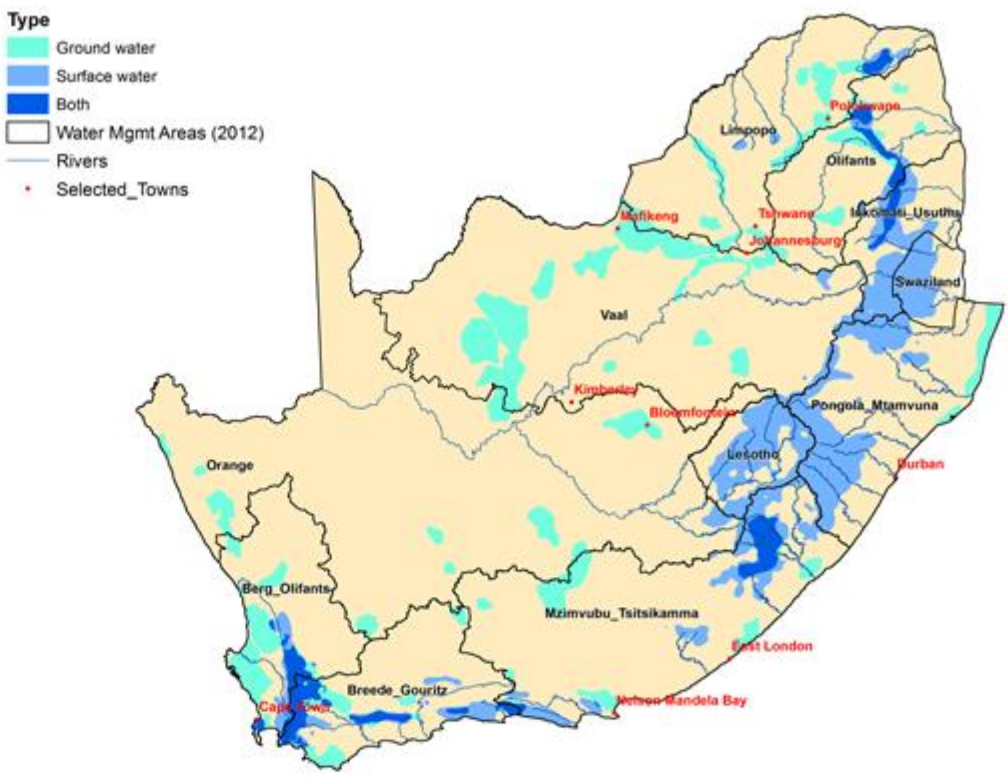

Figure 35: Strategic water source areas in South Africa (Le Maitre, et al, 2018).

3.3.2 Pollution sources

Pollution incidents is handled by the National Department of Environmental Forestry and Fisheries (DEFF) and its provincial counterparts, i.e. the Department of Environmental Affairs and Development Planning (DEA & DP) in the Western Cape. DWS only provides guidance and comments on the management of pollution sites. Groundwater pollution due to long-term releases of pollutants are often handled by DWS, in conjunction with the department's responsibility for environmental matters.

Groundwater protection with respect to potential pollution is done jointly by DWS and DEFF, i.e. EIA process for potentially harmful developments and water use licenses for storage or release of hazardous material.

3.3.3 Data flow

Data can be uploaded to the national databases run by DWS, but such upload is not mandatory. Access to data from various projects is therefore often difficult and thereby limiting the dataflow between the different institutions and activities related to the use and protection of the groundwater. The ideal is that the data flow should be from municipality to CMA or DWS, from the user to DWS and from the consultants to the municipalities and clients, and ultimately to DWS.

3.3.4 Funding

The supply water to all people at an acceptable level of assurance, quality and accessibility costs money – both in terms of capital investment into infrastructure and the operation and maintenance costs associated with water treatment, bulk water distribution and reticulation within human settlements. The criteria for setting the tariffs and the procedures are described in various legislation and regulations, notably the two water acts: i) the Pricing Strategy for Raw Water Use Charges (National Water Act) and ii) the Water Services Tariff Regulations (Water Services Act).

Water tariffs under the NWA are collected at two levels. The first is the Raw water tariff, which covers the bulk or raw water supply from DWS to water users, such as municipalities, water boards, and agriculture. The legal mandate for this is in Section 56 of the NWA. It is divided into three categories (DWS, 23 August 2019):

1. Raw water Use Charges, which includes charges for water resources management such as the protection, allocation, conservation, management and control of water resources and the management of water quality within a WMA;
2. Water Resource Development and Use of Water Works Charges, that covers the costs of planning, design, construction operation, maintenance, refurbishment, and improvement of Government schemes, including operation and maintenance;
3. Water Research Levy is the tariff set in respect of water research charges, levied on quantities of water supplied, or made available for use for various purposes. The charges are paid into the national Water Research Fund and used by the Water Research commission (WRC) to fund water-centred Research and Development.

The second level of tariffs under the WSA is paid to the municipality, water service provider or Water board for water provided to water users within the municipal boundaries.

The various charges in the pricing chain accumulate to the end user/consumer tariff. It is thus important to look at the pricing chain in its totality and to consider all the sub cost elements when the consumer tariff is evaluated.

- DWS sets its raw water price in terms of the NWA and National Pricing Strategy for Raw Water Use Charges
- Water Boards set bulk water prices in terms of the Water Services Act and prices are (in effect) approved by national government.
- Municipal tariffs in terms of a local tariff policy which must comply with nationally defined norms and standards.

Part of the tariffs collected for the water in South Africa is earmarked research in water. However, the funding for research covers all waters and as surface water is the main resource, the largest amount of money for research has also been directed towards surface water topics. No money is thus earmarked for groundwater research or to the general assessment and development of groundwater through national projects.

DWS administers two (2) conditional grants, viz., the Regional Bulk Infrastructure Grant (RBIG) and the Water Services Infrastructure Grant (WSIG). These grants support the predominantly indigent areas. The goal of the Regional Bulk Infrastructure Grant (RBIG) is to facilitate achievement of targets for access to bulk water and sanitation through successful execution and implementation of bulk projects of regional significance. The purpose is:

- to develop new, refurbish, upgrade, and replace ageing bulk water and sanitation infrastructure of regional significance that connects water resources to infrastructure serving extensive areas across municipal boundaries or large regional bulk infrastructure serving numerous communities over a large area within a municipality.

- to implement bulk infrastructure with a potential of addressing water conservation and water demand management (WC/WDM) projects or facilitate and contribute to the implementation of local WC/WDM projects that will directly impact on bulk infrastructure requirements.

The Regional Bulk Infrastructure Grant (RBIG) is intended to fund the social component of regional bulk water and sanitation projects approved by DWS, unless exemptions based on affordability are recommended by DWS and approved by National Treasury. All identified projects must be referenced to and included in the municipal Integrated Development Plan (IDP) and Water Services Development Plans (WSDP) and show linkages to projects under the Municipal Infrastructure Grant (MIG) and/or the Water Services Infrastructure Grant (WSIG). Funds may only be used for drought relief interventions based on a business plan approved by DWS. The goal of the Water Services Infrastructure Grant (WSIG) is to provide water and sanitation services and reduce backlogs. The purpose is:

- Facilitate the planning and implementation of various water and sanitation projects to accelerate backlog reduction and enhance the sustainability of services especially in rural municipalities.
- Provide basic and intermittent water and sanitation supply that ensures provision of services to identified and prioritised communities, including spring protection and groundwater development.
- Support municipalities in implementing water conservation and water demand management (WC/WDM) projects.
- Support the close-out of the existing Bucket Eradication Programme intervention in formal residential areas.
- Support drought relief projects in affected municipalities.

All project scope funded must be aligned to, and not duplicate, any existing or planned projects funded by other conditional grants or municipalities' own funds. Municipalities must demonstrate in their business plans how they plan to manage, operate, and maintain the infrastructure over the long term. The maximum allocation for WSIG projects is R50 million, any project above this threshold is to be funded in the Regional Bulk Infrastructure Grant. Projects should ideally be implemented over a year and the maximum period that a project can be implemented is three years.

3.3.5 Groundwater protection instruments

It is important to develop clear goals relating to the quality of the relevant water resources, so criteria are available for management of the resource. The NWA requires that a balance must be sought between the need to protect and sustain water resources on the one hand, and the need to develop and use them on the other. The Reserve, Water Resource Classes and Resource Quality Objectives are tools provided for in Chapter 3 of the National Water Act (Act 36 of 1998) to help with the protection of water resources, including groundwater. The Reserve consists of 2 parts namely the basic human needs reserve and the ecological reserve and refers to both the quantity and quality of the water in the resource and will vary depending on the class of the resource. The water resource classes are divided into three classes; i) a water resource which is minimally used and in which the configuration of the ecological categories of the water resources within a catchment result in an overall condition of that water resource that is minimally altered from its pre-development condition; ii) a water resource which is moderately used and in which the configuration of the ecological categories of the water resources within a catchment result in an overall condition of that water resource that is moderately altered from its predevelopment condition; and iii) a water resource which is heavily used and in which the configuration of the ecological categories of the water resources within a catchment result in an overall condition of that water resource that is significantly altered from its pre-development condition. The class of a water resource must describe the extent of use of the water resource, the Reserve, the resource quality objectives and the determination of the allocable portion of water resource for use.

The resource quality objectives of the resource in question may relate to the Reserve, the instream flow, the water level, the presence and concentration of particular substances in water, the characteristics and quality of the water resources and the instream and riparian habitat, the characteristics and distribution of aquatic biota, the regulation or prohibition of instream or land-based activities which may affect the quantity of water in or quality of the water resource and any other characteristics. It must be noted that these instruments are designed and implemented based on surface water behavior, scale and boundaries, and have limited applicability to groundwater.

3.4 Supporting infrastructure

The DWS has a number of databases, with the National Groundwater Archive (NGA) – successor to the National Groundwater Database (NGDB) containing most of the borehole related data. Data from reports were captured by the DWS on the NGDB. With the transition to NGA that is a web-based system, it has given external users the ability to capture and extract data themselves. The data that is collected from groundwater assessment projects are seldom captured as it is not mandatory to upload the data to the national databases, neither is legislation in place for enforcing this. This means that data are not readily available for use in subsequent groundwater mapping and assessment exercises. Currently efforts are being made by the DWS to source data and reports from relevant stakeholders.

Data for the most part tend to be collected by consultants during projects for clients. These data are stored by consultants and only shared with DWS on request, with permission from the client. To access data from consultants may be difficult and some are unwilling to share their data –also sometimes not with their clients. Models tend to remain the property of the consultants or in some cases their clients.

Data storage on the national level is done in a number of databases – NGA for borehole data; Hydstra for water levels; Water Authorisation and Registration Management System (WARMS) for water use and revenue collection; and Water Management System (WMS) for water quality data. Same municipalities have their own databases to capture their own data. Data storage can also be done by the consultants.

NGA data is available to the public through a web-based program if they have registered to use the system. The other databases are not open to the public, but a request can be sent to DWS to get the data.

The geophysical data are not captured on a national database as yet. DWS is in the process to develop the functionality on NGA. Most data reside with the consultants or are hard copy reports. It is thus not readily available for use. Non-disclosure agreements between clients and consultants are signed, meaning that no data nor any information regarding the specific project may be provided to other parties without consent. Thus, often a legal process has to be followed to access the data.

There are no set structure or mandate on how groundwater mapping and assessment should be done in South Africa. A number of guidelines have been produced and reports written on the best way to do groundwater assessments for wellfield developments, but it is not mandatory to follow these guidelines. Furthermore, the various guidelines are not centrally stored, which can make be difficult to identify the latest version and some has to be paid for.

Research infrastructure includes the various universities and the Water Research Commission that supports and funds groundwater related research.

4. COMPARISON OF APPROACHES

In order to fully understand, and thus compare, groundwater mapping and assessment programs in Denmark and South Africa, a number of key factors have been identified. These key factors are seen as the internal and external forces that drive and shape the mapping and assessment activities and the characteristics of the program.

The key factors for this project are divided up into four different groups: drivers, institutional factors, supporting infrastructure and key characteristics. The drivers are the circumstances driving the need for groundwater mapping and assessments, which are founded in both technical and societal issues. The institutional factors include the policies providing the legal and institutional framework necessary to implement the mapping and assessment. The key factors for supporting infrastructure includes the developed methods, tools and resources that make it possible for the mapping and assessments to meet the political ambitions. The key characteristics are activities and results/output from the groundwater mapping and assessment.

The relationship between the key factors is shown in the diagram presented in Figure 36. Understanding this relationship is important when analysing and comparing groundwater mapping and assessment activities in Denmark and South Africa.

The drivers are seen as the factors that create the need for groundwater mapping and assessment; it is in essence the situation the country is in. This includes, for example, the degree in which a country or region is dependent upon the groundwater, the natural and human threats to the quality and quantity of the resource, and the different users of the resource, including municipal, industrial, agricultural and nature. The interaction between these creates a situation where there is a need for the management of groundwater resources. This need, then drives the creation of policies towards the management and protection of groundwater resources, as illustrated in Figure 36.

The policies that are taken create the institutional framework from which groundwater mapping and assessment takes place. Policies generally start with the creation of a strategy on how the needs for groundwater management and protection should be dealt with; in essence what should be done. From the agreed strategy, legislation is passed putting the strategy into law, and in turn also provides the funding for the activities. This in turn determines how the activities should be organised and who has the responsibilities to carry out the mapping and the standards that need to be achieved. These aspects can change over time, particularly as the situation driving the groundwater mapping and assessment changes.

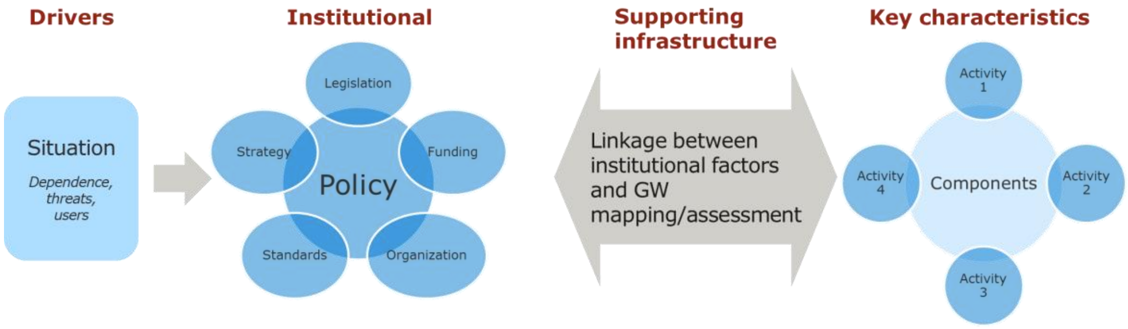

Figure 36 Diagram showing the relationship between the different key factors in the groundwater mapping and assessment activities.

The supporting infrastructure provide the link between the policy and actual mapping and assessment activities. This includes e.g., the databases, tools and guidelines that are available. These provide the guidance to what should be included in the groundwater mapping and assessment activities as well as tools and software that can be used to support the assessments. The development of the infrastructure, tools and guidelines are determined through the policy decisions taken.

Finally, the key characteristics are the actual mapping and assessment activities that are undertaken within the groundwater mapping and assessment programs. Included in the key characteristics are what is actually conducted and the type of results that are obtained from the mapping and assessment. Mapping and assessments can be carried out for various purposes, which will define the relevant activities. However, here we define mapping as: Activities related to the analysis and understanding of the groundwater system. The analyses are based on existing and newly collected data. Although mapping to some degree is targeted towards a specific challenge related to groundwater quantity and/or quality, it contains generic steps that needs to be carried out, independent on the final assessments. On the other hand, activities related to the assessment are specifically targeted the objective of the assessment. We define assessment as: Utilising the mapping results in the planning and protection of the groundwater resources. This includes assessments on the quantity available, where protective measures securing groundwater quantity and quality need to be taken place, and possible activities such as monitoring and groundwater protection initiatives.

Assessing the links between the key factors, as shown in Figure 36, can help identify where there are gaps or incongruities between the different key factor groups. For example, the policies outlined in the institutional key factors may not be implemented due to a lack of development in the supporting infrastructures. Thus, by linking these different groups, weak points in the process can be identified.

4.1 Key Factors - Denmark

The following are the key factors that have influenced groundwater mapping and assessment programs in Denmark. The diagram in Figure 37 shows the relationship between the key factors in Denmark. This starts with the drivers, where there is a nearly 100% dependence on groundwater for the water supply, combined with threats from pollution. From these threats, there has been developed a strategy that Denmark's water supply should be based upon simple treatment. From this strategy, legislation has been implemented outlining the objectives, funding, organisation and standards. The legislation has also provided the groundwork for the development of the supporting infrastructure, including staff dedicated to the mapping and assessment activities, mandatory data collection and availability, development of specialised tools to assist with the activities and the development of the supporting guidelines. This has provided groundwork for the three different groundwater mapping and assessment programs in Denmark, as described in section 2 and illustrated in Figure 37.

A more detailed description of the key factors associated with groundwater mapping and assessment in Denmark is provided in sections 4.1.1 to 4.1.4 below.

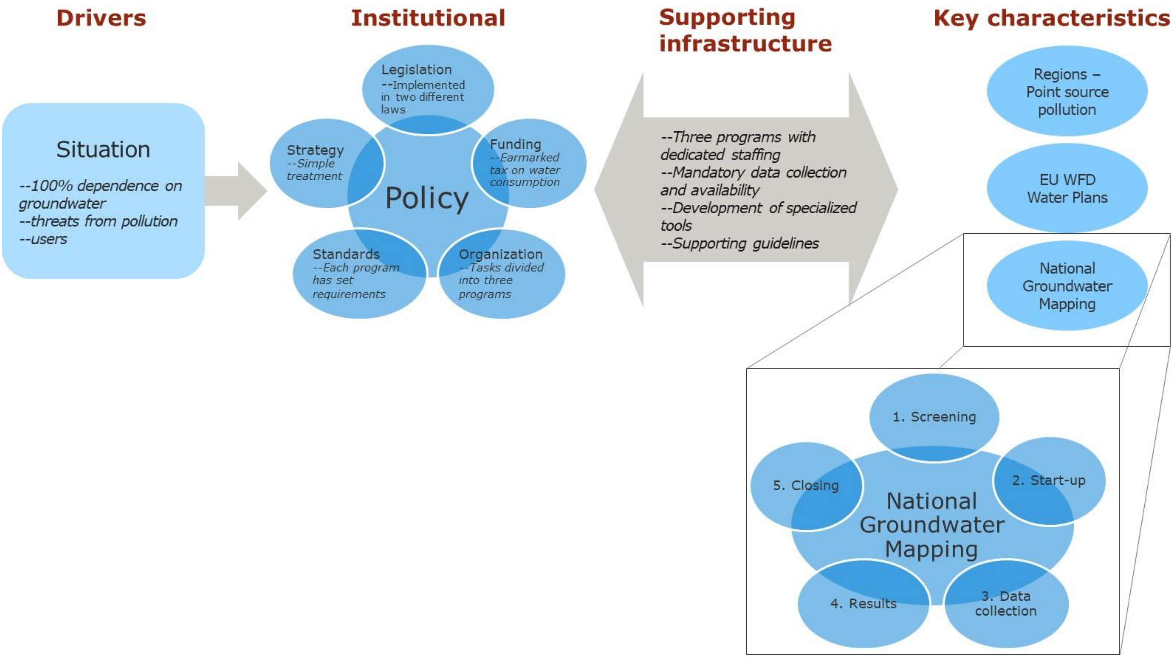

Figure 37 Diagram showing the relationship between the key factors in Denmark.

4.1.1 Drivers

The following are the key factors that are the primary drivers for groundwater mapping and assessment in Denmark.

1. Reliance on groundwater:
   Nearly 100% of drinking water in Denmark comes from groundwater, and the largest part of water for industry and agriculture.
2. Threats to the groundwater quality:
   The primary driver that started the Danish groundwater mapping and assessment was the observation of increasing pollution of the groundwater resources from particularly agriculture (nitrates and pesticides), but also from point sources including industrial sites and landfills, as well as abstraction induced saltwater intrusion and naturally occurring ions such as fluoride, nickel, strontium and arsenic.
3. Water balance:
   Denmark has a relatively high amount of groundwater recharge, where quantity generally is not an issue. There are, however, some local and regional aquifers where abstraction has an impact on baseflow in streams and groundwater dependent ecosystems.
4. Users:
   The primary users of groundwater resources in Denmark are private and municipal water supply companies providing drinking water to domestic consumers. These users require a water supply that meets a high water quality that meets or exceeds EU water quality standards. In addition, there are also industrial consumers that require a certain water quality.

5. Ownership:
   Groundwater resources are owned by the state and always have been. All users need permission to use the resources, and it is the state's obligation to protect the quantity and quality of the country's groundwater resources.

4.1.2 The institutional key factors

1. Simple treatment:
   Denmark has maintained an overarching policy that drinking water provided to the consumers is based only on a simple water treatment consisting of oxidation and sand filtration. Although advanced water treatment techniques, such as active carbon filtration and reverse osmosis have been used in drinking water treatment, this is only permitted when there are no other alternatives. Thus, this policy has been a key driver in the groundwater mapping and assessment program.
2. Legislative framework:
   In order tackle these groundwater quality problems, legislation was enacted at the national level, ultimately enacting a levy per cubic meter withdrawn by the waterworks. The legislation was vital, since it required that the areas that should be protected be defined and gave the legal framework for restriction of activities that could compromise the groundwater quality. In addition, it provided the legal requirement for both the studies on the groundwater systems that need to be carried out and the development of the subsequent Groundwater Protection Plans. The legislation also developed the requirements for data gathering, storing and sharing at all levels. In addition to the national legislation, there is also requirements from the EU, particularly with the EU Water Framework Directive, where both the quantitative and quality for both human and ecosystems are considered.
3. Funding:
   Critical to the legislative framework was the inclusion of the groundwater levy in the legislation. This levy on every cubic meter of groundwater pumped by the waterworks, is essential to providing the needed resources to carry out the groundwater mapping as well as support for the development of the techniques, guidelines, tools and data storage platform (including operation and maintenance).
4. Organisation:
   The Danish groundwater mapping and assessment is divided up into three main program units. This includes groundwater mapping, which looks at the protection of groundwater quality from non-point source pollution, EU Framework Directive Water Plans, which looks primarily at groundwater quantity where environmental needs (ecosystem needs) are also taken into consideration, and the Regions mapping, assessing and remediating point source pollution.

4.1.3 Supporting infrastructure key factors

1. Capacity building:
   The critical part of this was to generate the institutional capacity to conduct the groundwater mapping in Denmark. As directed by the Danish Legislation, initially the counties in Denmark were responsible for conducting the groundwater mapping and executing the groundwater action plans. During this time, the counties built up the needed personnel and expertise to conduct the mapping and assessment. After the governmental structural reform in 2007, this capacity was transferred partly to the state to conduct the mapping and partly to the municipalities to develop and execute the action plans.
2. Data collection, storage and access:
   All data collected through the groundwater mapping and assessment is assembled and stored in their respective databases. The state operates and maintains these databases, and all public and private institutes and stakeholders have free access to this data. This

includes all data required to be delivered by law, including water level measurements, water quality, abstraction amounts, borehole reports, geophysical data, stream measurements, models and model results and reports. Data is well organised, easy to find and available for all users.

3. Development of specialised tools:
   A part of the funding was provided to develop specialized tools to assist with the groundwater mapping and assessment process. This development has primarily been done by the universities but also consultants have been funded in this respect. The geophysical methods developed helped to fill in data gaps, and the software developed assisted in efficient processing of geophysical data and development of a new 3D geological modelling software that can directly incorporate the data from the national databases.
4. Development of the guidelines:
   The development of the guidelines was critical in assuring that the mapping and assessment was conducted to a uniform and high technical standard. This includes methods and standards for data collection, modelling and risk assessment processes. The guidelines actively used by both the Danish EPA and consultants to assure that groundwater mapping and assessment is consistent across the country.

4.1.4 Key Characteristics

1. Three approaches:
   Groundwater mapping in Denmark is divided into three approaches, each with their deliveries.
   a. Groundwater mapping: provides a detailed assessment of the geology, hydrology, groundwater chemistry and groundwater modelling, resulting in the delineation of the well head protection areas, well field catchment areas and groundwater vulnerability to nitrates and pesticides.
   b. EU Water Framework Water Plans: has the aim to protect all waters, i.e., to preserve and enhance the status of aquatic ecosystems related to both quality and quantity. Hence, resource use assessment is carried out to identify areas with sustainable/unsustainable groundwater use
   c. Danish Regions point source pollution mapping, assessment and remediation.
2. Data sharing:
   Even though groundwater mapping and assessment is divided up into three separate programs, data collected and produced in the three different programs is readily available and used in the other programs.
3. Results used in groundwater management:
   The municipalities are responsible for development and implementation of groundwater management and protection plans as well as permitting and control. These plans are based directly on the results from the three mapping and assessment programs, where the data collected provides input to the actions and decisions taken for groundwater protection.
4. Data coverage:
   Denmark has a very high density of data which can be used in groundwater mapping and assessment. This starts with a relatively high density of boreholes in the country. With over 300.000 boreholes registered in Jupiter database, there is an average of 7 boreholes per square kilometre. In addition, there has also been collected a high spatial coverage of geophysical data in connection with the groundwater mapping. As an example, nearly 80% of the area of the island of Funen is covered by the different geophysical surveys, see Figure 38. Particularly airborne electromagnetic surveys (SkyTEM), developed in conjunction with the Danish Groundwater Mapping Project, has provided significant coverage over large areas.

5. Model development:
   At a very early stage, the Danish groundwater mapping projects began developing both digital 3D geological/hydrostratigraphic models and hydrological models. Nearly the entire country is now covered by a 3D hydrostratigraphic model, and efforts over the last two years has coupled these models so that there is a continuity in the geological layers between the different models. In addition, nearly all local groundwater mapping areas have incorporated results from 3D groundwater models, from which recharge and well-field catchment areas are calculated. In addition, there are the 7 large-scale 3D regional hydrological models which cover the entire country, apart from some of the smaller islands.
6. Co-interpretation of data:
   During the groundwater mapping, there are several different types of data collected and different types of results used in order to come up with a concluding assessment. This includes geological data, hydrological data, groundwater quality, groundwater modelling results, land use, and mapped contamination. These results are all combined in one analysis for the resulting vulnerability assessment identifying where protective actions should be taken.
7. Scale:
   Individual groundwater mapping and assessment projects are generally carried out in smaller mapping areas, often covering only one or two municipalities, totaling 100-500 km^2, with the largest areas being around 3,000 km^2. Thus, groundwater models from these mapping areas tend to be local to small regional models. However, the results combined cover at least half of the total area of Denmark (43,000 km^2), and nearly all of Denmark is covered by a geological model. The mapping and assessment activities conducted in association with the EU Water Framework Directive water plans are conversely on a larger regional scale, where four water basins have been defined, but with results covering the entire country.

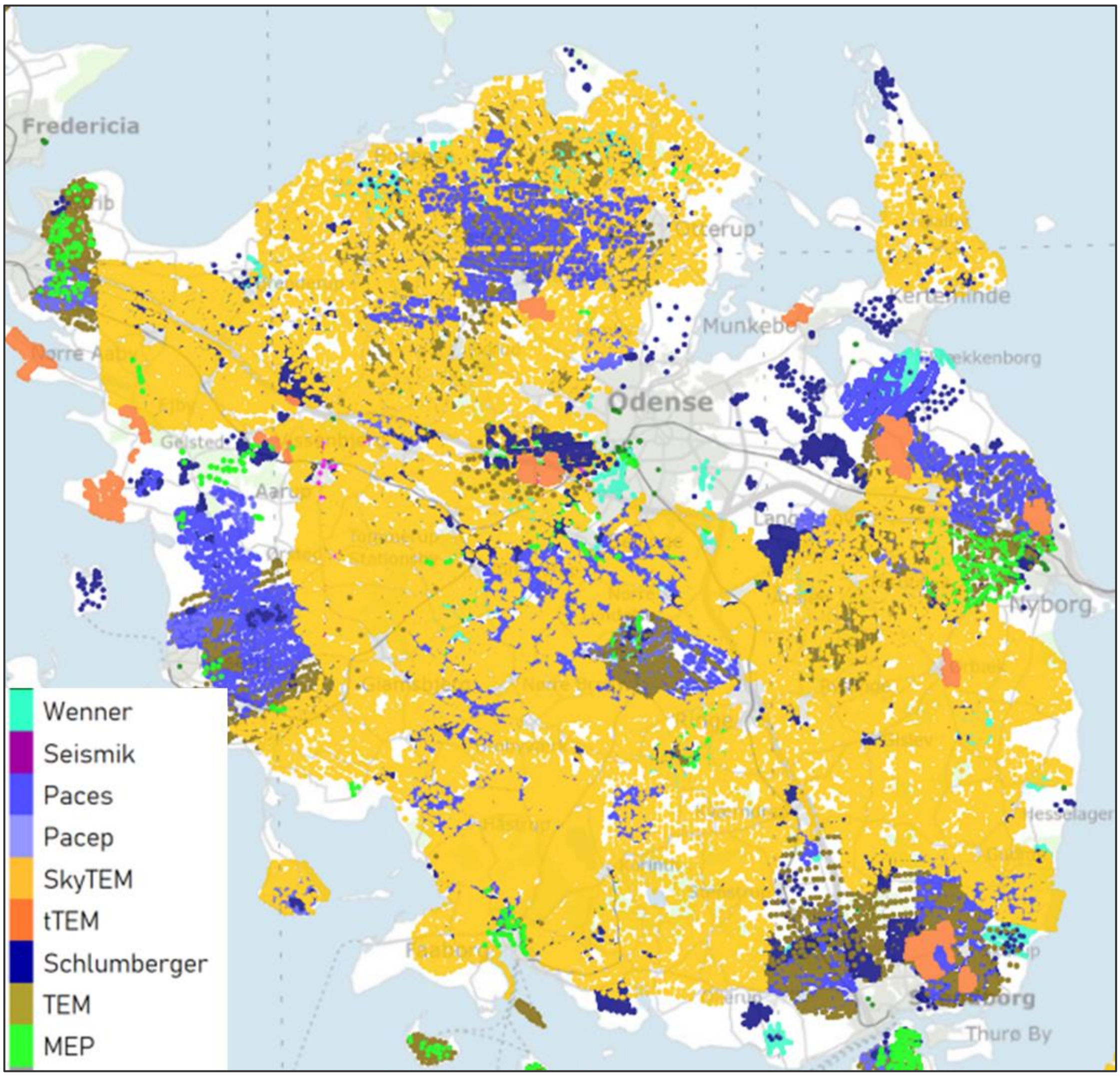

Figure 38 Coverage of geophysical data for the island of Funen.

4.2 Key Factors – South Africa

The relationship between the key factors and key characteristics for South Africa is illustrated in Figure 39. Like for the Danish conditions, different studies can be carried out with different purposes, i.e., the construction of new wellfields, assessment of the quantity of groundwater or the protection (under Key Characteristics), which each include different activities. The key factors within each category: Drivers, Institutional, Supporting infrastructure and Key Characteristics are detailed in the sections below.

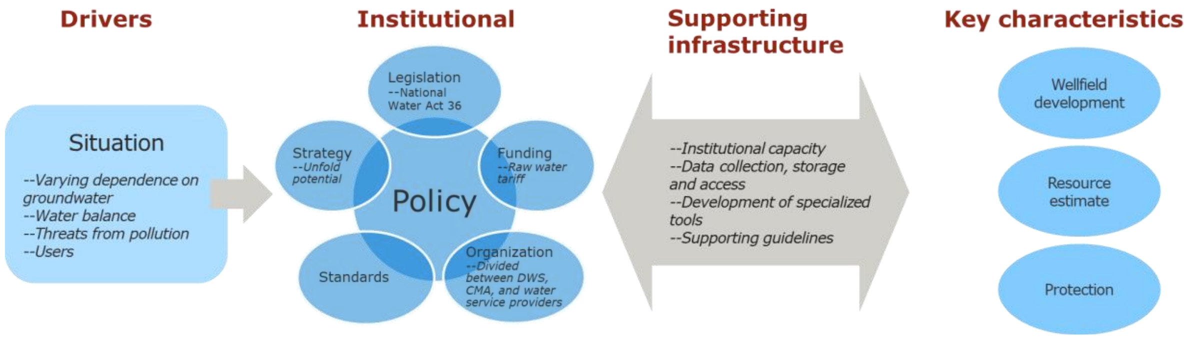

Figure 39 Diagram showing the relationship between the key factors in South Africa

4.2.1 Drivers

The following are the key factors that are the primary drivers for groundwater mapping and assessment in South Africa.

1. Sources of water:
   South Africa is reliant on surface water for most of its water supply. Although the groundwater supplies only 8% of all the water in volume, more than 50% of smaller towns are either solely reliant on groundwater or surface water and groundwater is conjunctively used for water supply.
2. Threats to the groundwater:
   The quality of groundwater in South Africa is very variable and linked to the geology and other natural processes. It is thus possible to have naturally occurring pollutants in addition to pollutants from human sources. Pollutants from human activities are mainly in the form of diffuse pollution from agriculture and point source pollution from industries, mining, and filling stations. These have an impact on the water quality and can influence the quality of the resource for future generations. Over-abstraction and its associated consequences are a threat to groundwater quantity (see 'Water balance' below).
3. Water balance:
   South Africa has a variable amount of groundwater recharge depending on factors such as precipitation volumes and geology. The western half of the country tends to be semi-arid to arid with rainfall below the world average. High evapotranspiration rates, often higher than precipitation, exacerbated by high temperatures and wind further reduce recharge. Recharge to groundwater tends to be periodic, associated with above average rainfall events in these areas. Rainfall and recharge in the eastern part of the country tends to be seasonal, with lower evaporation.
4. Users:
   Groundwater users have different requirements. Irrigation, accounting for nearly 60% of the total groundwater abstracted, does often not set the same requirements to the water quality as potable water, but are more concerned on a sufficient supply, especially during drought. In rural towns and on private properties with wells where groundwater is used without treatment, a high quality is, on contrary, a prerequisite, while some treatments are often associated in larger cities where the bulk water resource is from surface water.
5. Ownership:
   Prior to the National Water Act of 1998 (Act 36 of 1998) the groundwater was a private entity, where the landowners had water rights, and thus the privileges to utilise the resource without a permit. With the National Water Act of 1998 (Act 36 of 1998) the water resource became a public entity with the national government being a custodian and responsible for the allocation of the resource. However, the authorisation depends on the amount of water

used and the potential impact of the water use. Small scale use falls under Schedule 1 use, e.g., household and small stock watering, and does not require a registration.

4.2.2 The institutional key factors

1. Strategies:
   Several national strategies have been developed in which visions and goals for groundwater use have been formulated. Three National Groundwater Strategies were developed since 2000 (2003, 2010 and 2017), which were incorporated into the National Water Resources Strategies (NWRS1 – 2004 and NWRS2 – 2013). While the NGS considers both the qualitative and quantitative challenges more emphasize is given to quantity as five out of seven objectives for the NGS are related to how best to unfold the potential of groundwater to secure the water supply, while one is related to quality. This reflects that most important for the utilisation of the groundwater is the presence of the source, while poor quality can be treated, which is already common practice in the use of surface water.
2. Legislative framework
   Groundwater quality for various uses is guided mainly by the South African National Standards (SANS) and guidelines by the Department of Water and Sanitation. Groundwater mapping and assessment is supported by the latest Groundwater Strategy from the Department of Water and Sanitation. Groundwater was private property until the National Water Act (Act 36 of 1998) was promulgated. Groundwater became a public entity under the care and protection of the Minister of the Department of Water and Sanitation. The management of the water resources were delegated to local level.
3. Funding
   There is a raw water tariff that includes raw water use charges and Water resource development and use of waterworks charges. Beyond paying the administrative management, a levy is also allocated for water related research through the Water Research Commission (WRC), but it is not specifically targeted towards groundwater mapping.
4. Organisation:
   DWS is responsible for providing the legal framework for the governance of the water resources, providing raw water to the water services authorities and the national mapping programs. The Catchment Management Agencies (CMAs) are responsible for implementation of the legal framework and for water use authorisations. They also collect tariffs from water users outside the municipal supply system, such as water users' associations and irrigation boards. Water services authorities, such as water boards, District Municipalities and Local Municipalities, are responsible for the treatment of raw water to potable standards. Water Service Providers – usually the local municipalities – are responsible for the reticulation systems, sanitation and wastewater treatment and collection of tariffs.

4.2.3 Structural Key Factors

1. Capacity building:
   Institutional capacity is one of the most important challenges when it comes to groundwater mapping and assessment. The Department of Water and Sanitation currently has limited capacity, with the bulk of the increased capacity within the private sector or consultancies. Not all municipalities have the capacity to effectively develop, manage, and assess their groundwater resources nor to perform in-house mapping. The City of Cape Town is one of the only municipalities that have employed dedicated hydrogeologists, the rest contract consultants. The importance of capacity building is stressed in most of the strategies but have not yet been fully developed.
2. Data collection, storage and access:
   Data used for groundwater mapping and assessment must be sourced from various sources.

This includes geological maps, hydrogeological maps, reports, borehole information from the National Groundwater Archive (NGA) (previously the National Groundwater Database (NGDB)), water levels (Hydstra), water quality from the Water Management System (WMS), geophysics, aquifer yield and borehole yield from pumping test data (NGA & reports), stream measurements (Hydstra) and water use registrations from the Water Use Authorisation and Registration Management System (WARMS). DWS manages the databases (NGA, Hydstra, WMS and WARMS), including capturing the data and sharing the data on request. The only exception is the NGA which is web based and where it is possible for registered users to extract and upload data. Municipalities, water users' associations, consultants, etc. tend to have their own databases that are not aligned to that of DWS and are not available to the general public.

3. Development of specialised tools:
   A number of software programs were developed for groundwater related applications, such as the Flow Characteristic program (FC method) for the analysis of pumping test data, the GRDM (Groundwater Resource Directed Measures) software for groundwater management in Karoo aquifers, Aquiworx, and many other software for the interpretation of groundwater relate data and processes. Most of these have focused on fractured rock environments, while far less have been developed with porous aquifers in mind. Different recharge estimation methods were also developed in South Africa such as the Cumulative Rainfall Departure (CRD) method. Many other tools for analysis have been developed as part of WRC projects, but has not found general application yet.
4. Development of guidelines:
   Guidelines and standards on assessment, development, and protection of groundwater have been developed by the Department of Water and Sanitation, through research projects funded by the WRC or the SABS (South African Bureau of Standards). The guidelines are not stored centrally and identifying the most recent version can be difficult. People are often not aware of the guidelines, or they are not willing to pay for it. The use of guidelines is generally not enforced and often they are disregarded. In addition to guidelines, standards have been developed, such as the South African National Standards (SANS) for drilling, pumping tests and water quality standards. The SANS for drinking water quality is implemented and enforced.

4.2.4 Key Characteristics

1. Mapping at different scales:
   Mapping consists of the assessment of subsurface properties, potential groundwater resources and challenges. The DWS is mainly responsible for national and regional mapping. The DWS relies on data and information sources from DWS databases, hydrocensus work, consultants and other sources. The Water Resource Classes, Resource Quality Objectives and Reserve is in place to protect the quality and quantity of groundwater, with groundwater protection zones set to be implemented in future. At regional/local scale mapping is often carried out as part of an assessment carried out to identify a suitable location for the development of water abstraction wells and assess the suitability of the water resource. It is done at different scales reflecting the amount of water required and may thus cover a large area. The mapping is, however, targeted the specific objectives of the assessments and not part of a groundwater mapping aiming at a general evaluation or protection of the groundwater.
2. Data sharing:
   Data is available for DWS databases, mostly through requests. The NGA is the only databases that is accessible to the general public, with the option for consultants and others to update the database. Hydstra, WMS and WARMS are managed by DWS. Data from these

databased are available on request. It is not compulsory to share data with DWS or to capture the data on the NGA. This is also true for geophysical data, models and reports.

3. Results used in groundwater management:
   The results of groundwater assessment programmes – mostly from the assessments carried out as part of the development of a wellfield, with the results of GRA I and GRA II playing a minor role – and the monitoring that takes place during the operations at the wellfields are used in the management of municipal wellfield. Regional and national assessments, being large-scale activities with inherently coarser scale resolutions, has thus far played a very small part, if at all, in the management of groundwater resources at the local scale. They do play a role in planning on a national and regional scale, and were used in the different Reconciliation Strategies, e.g., the All Towns Reconciliation Strategies.
4. Data coverage:
   The NGA holds more than 255 000 borehole records and an additional 11 000 other geosites. A major contribution to the database was during the investigations that led to the production of the national hydrogeological maps between 1992 and 1996. The density of the borehole records varies across the country, with high densities around large exploration projects, such as Cape Flats, Atlantis and the Lower Berg River area, but almost no data for other areas. The average borehole density is 0.2 boreholes per square kilometre. The NGA data record has not kept up to date with the drilling for groundwater, due to the sheer number of boreholes drilled annually and the fact that it is not compulsory to provide DWS with the data or to upload the data to the NGA. Approximately 100 000 new boreholes are drilled each year by private individuals but are not uploaded to NGA. An average of 720 new sites been uploaded each to the NGA (average from 2015-2021).
   The coverage of geophysical data is limited and tend to be localised transects connected to specific projects and/or to determine the best site for the drilling of production boreholes. The geophysical module in the NGA is in process and will be available in 3-4 years. The fracture rock aquifers lean towards more localised investigations because of the complexity of the geology. Geological maps/information and structural analysis are used to identify areas of investigation to do detail geophysical survey. Large scale geophysics has only been undertaken recently in connection with wellfield development projects to address the impact of the drought. Examples of this is the airborne geophysics carried out by the City of Cape Town around the Cape Flats and Atlantis, and the work done by SkyTEM for Ramotswa and Saldanha Bay Local Municipality on the coastal aquifers around Saldanha. Same reports are logged onto library called the GH Report system and are freely available for the public to download. The data within the reports are not captured onto the NGA. The reports from water use licence application process are not captured onto the GH Report system.
5. Development of 3D models:
   When groundwater flow models are developed, they are in most cases based on a simplified geology without detailed geological/stratigraphical modelling (no voxel model). The development of 3D geological models is only done by a small number of consultants, and especially applied when they are working with very complex geologies. Models are predominantly used to evaluate the productivity of new wells/wellfields in feasibility studies based on pumptests from newly developed production wells. Consultants are free to choose their own modelling software. There is no modelling standards or guidelines developed to account for specific South African conditions, which thus rely on international guidelines and best practice.
6. Co-interpretation of data:
   Different data types are combined in the assessment and mapping of groundwater, i.e., when developing a hydrocensus. This includes topographical, geology, and hydrogeological maps on different scales. Data sets from the different databases and reports of previous studies include geology/lithology of boreholes, geological structures, yields, water strike,

recharge, storage, quality, water level measurements, stream flow measurements and climate data.

7. Scale:
Assessments for the development of individual abstraction wells or small wellfields generally have a limited areal extend and may not include detailed subsurface mapping/geological interpretations. Explorations for large scale waterworks may cover local to regional areas, i.e., tens to hundredths square kilometres, and mostly include more detailed investigations. At the largest scale, the national mapping covers the entire country and cannot include all details found at the local scales. Knowledge thus exists at different scales, national, locally/regional and points, and while the national studies per se covers the entire country, the studies at smaller scale are rarely combined to provide detailed interpretations for larger areas.

4.3 Similarities and dissimilarities in approaches

The key factors are compared one-to-on in Table 3, followed by an evaluation on how differences in the approaches have contributed to the differences observed in the two approaches.

Table 3 Comparison of key factors in Denmark and South Africa.

Drivers - Situation	
Denmark	**South Africa**
100% reliance on groundwater for municipal water supply.	Heavy reliance on surface water, but groundwater constitutes the main or sole supply outside surface water distribution networks, often in urban areas and smaller towns. Groundwater is historically considered a secondary unreliable resource.
Groundwater quality threats – initial primary concern has been diffuse agriculture pollution but point source pollution also considered. Natural pollution sources from geology are generally limited and local, with some introduced by overexploitation.	Quality issues are related to both diffuse (agricultural), point sources and natural pollution from the geology. This phenomenon is widely spread throughout South Africa as dominated by the type of geology.
Generally sufficient recharge and only local groundwater quantity issues, particularly considering freshwater ecosystems.	Groundwater quantity is limited due to both limited precipitation in some areas and a complex aquifer system where the yield is often low.
Primary users are private and public municipal water supply companies (59%), agriculture (32%) with a minor amount for industry (9%).	Users spans from private well-owners to large municipality water supply (13%). Agriculture is the largest groundwater users in terms of quantity (65%).
State has ownership of all groundwater rights in the country.	The state is the custodian of all water resources, while water is a public entity. The public can apply for water rights, although the state determines whether or not they are entitled to exercise or make use of the water right.
Institutional - Policy	
Denmark	**South Africa**

Strategy that drinking water should be based on simple treatment and thus a public focus on clean water supply.	National strategies include the protection of groundwater but have most focus on unfolding the potential of groundwater as a reliable resource. With dependency on surface water, purification of portable water is standard.
Legislation mandates groundwater protection.	National activities are supported by the national strategies, but legislation does not provide mandate for carrying out groundwater mapping.
Funding for groundwater mapping and assessment set in legislation in the form of a per m^3 levy (tax).	Funding through levy on water consumption, used to pay for the water distribution network administration and general water resources research. There is currently not dedicated funding for groundwater mapping; however, DWS initiated a process to realise funding in the near future.
Mapping and assessment are divided among different actors: the state - assessing vulnerability to non-point source pollution; regions - dealing with point source pollution and state/EU - dealing with groundwater abstraction impacts on aquatic ecosystems.	Only the state is responsible for a general mapping and assessment, which is realized in targeted projects. The authorities below the state may conduct assessments to develop wellfields but are not responsible for a general mapping or protection.
Supporting infrastructure	
Denmark	**South Africa**
Programs and staffing dedicated to groundwater mapping and assessment programs.	High competences by consultancies while capacity among other key actors varies and at some levels are limited.
All governmentally collected data, models and reports are publicly accessible from national databases.	Public access to data in NGA. Other public data available on request, except for some reports while no models are stored centrally. Not all data collected in state funded projects are uploaded to national databases.
The national groundwater mapping program has included resources for developing specialised tools and software.	Specialised methods and software have been developed as part of general water research projects.
Guidelines developed as part of the mapping program and integrated into the process to assure high and consistent quality.	Several guidelines have been developed but are not fully integrated in the mapping and assessments.
Key Characteristics	
Denmark	**South Africa**
Three separate approaches for the different areas rather than one unified groundwater mapping and assessment program.	DWS are responsible for national mapping and assessments, while local/regional activities are predominantly focusing on developing specific water supply systems, and not mapping for more general purposes.
Data are shared between the different programs, agencies, as well as available for municipalities and other stakeholders to use.	Data stored in national databases are made available by DWS, while data collected by

This data is widely available, free of charge, through the publicly accessible databases operated by the state.	consultants in customer paid projects often are not freely available.
Results are used actively in groundwater management and planning.	Results from mapping and assessments are used actively in groundwater management and planning.
A high-density data coverage across the country, including borehole and geophysical data.	Data available across the country but varies in density.
Development of local and regional 3D geological and groundwater models, covering nearly the entire country.	Development of local and regional groundwater models often relies on simplified geology. Detailed 3D geological models are primarily used to clarify complex geology.
Co-interpretation of hydrology, groundwater chemistry, geological and groundwater modelling data.	Several data types are combined but co-interpretation of hydrology, groundwater chemistry, geological and groundwater modelling data is limited.
Mapping generally carried out for smaller areas, but together they cover most of the country, which has been combined into one national interpretation. However, the country is approximately 30 times smaller than South Africa.	Mapping has been carried out nationally. With the size of the country, such mapping cannot cover all details. Mapping is also carried out as part of smaller scale projects, but integrated into the national scale mapping.

4.3.1 Drivers

A comparison of the drivers for groundwater mapping and assessment in Denmark and South Africa reveal stark dissimilarities between the two countries. Starting with reliance on the resources, being a lowland, island and peninsula country, Denmark has a lack of sufficient and reliable surface water resources. Thus, groundwater is virtually the country’s sole source of water for drinking, agriculture and industry. In contrast, surface water has traditionally been the most important water resource in South Africa supplying water to cities and areas with high population density within the surface water distribution network. In less populated areas, such as rural areas and towns, groundwater often comprise the main or sole resource. Nevertheless, in terms of quantity the surface water is by far the largest resource and in relation to water supplier, groundwater has been considered a secondary and unreliable resource.

In Denmark, there is sufficient and stable precipitation across the country, where challenges with groundwater quantity are restricted to only some local areas and related to adverse effects on groundwater dependent ecosystems. Therefore, the question in Denmark is not if there are sufficient resources to abstract, but rather where the resources can be abstracted so that they will not adversely affect the water quality and groundwater dependent ecosystems. In contrast, South Africa has widely varying precipitation across the country and is susceptible to extended droughts. This greatly affects the availability of surface water, while groundwater with its buffering capacity can provide a more robust water resource. However, groundwater recharge, and thereby groundwater availability, is similarly affected by the large spatial variation in precipitation resulting in spatial variation in the groundwater resource. This is further amplified by the complex groundwater systems, where groundwater in some places is associated to discrete features, i.e., fractures, dykes etc., and thus difficult to map and utilise, or the groundwater bearing units are associated with low yields.

Denmark is a very agriculturally intensive country, resulting in many groundwater aquifers becoming polluted with fertilizers (nitrate) and pesticides across the country. Point source pollution from industry and landfills are also a local problem. As the primary use of groundwater in Denmark is for drinking water, which needs to be of a high quality, this puts threats to the groundwater quality directly into the spotlight. In South Africa, groundwater pollution is primarily on a local scale, though also from agriculture and industry. Agriculture has the primary use for the groundwater resources, but abstraction for clean drinking water is rising. Groundwater aquifers are mainly polluted by nitrates due to agricultural activities. Point-sources that are most often associated with urban settings and thus more local in impact.

Important to also recognise is the historical ownership of the groundwater resource. In Denmark the resource has always been a public good and a permit is required for all water usages, which is thus registered.

These different drivers have resulted in different purposes for groundwater mapping and assessment. In Denmark, groundwater mapping and assessment has had a primary focus on groundwater quality and the need to protect the groundwater resources for current and future generations. On the other hand, the groundwater mapping and assessment in South Africa has had a focus on the water quantity, with a focus on groundwater recharge, availability and well yield.

4.3.2 Institutional - Policy

In Denmark, the primary political strategy has been that Danish groundwater should be supplied with only simple treatment of oxidation and filtration. This has resulted in legislation that focuses the groundwater mapping and assessment on groundwater protection, including dedicated funding for national groundwater mapping and assessment programs.

In South Africa, the primary strategy has been to increase the use of groundwater in order to provide a more resilient water supply, particularly during drought conditions. Legislation in South Africa has been passed to support the national strategies, but does not mandate groundwater mapping and assessment at the national scale. Funding is designated the entire water resource of which groundwater constitutes a minor part. The funding allocated groundwater primarily goes towards the development of new well fields and infrastructure, administration for issuing permits and support general water resources research. Currently, no continuing funding is earmarked a more general groundwater mapping and assessment with the aim of protecting a future resource.

The differences in policies between the two countries are clearly derived from the differences in the drivers. Denmark's policies defining the purpose of groundwater mapping and assessment are clearly defined by the need to protect the groundwater quality. Although groundwater quality is considered, South Africa's policies are focused more on the increased use of the groundwater resource, stemming from the increased pressure on and unreliability of its surface water resources.

4.3.3 Structural support

In Denmark, there has been established state-run programs with dedicated staffing specifically to run the national groundwater mapping and assessment. Guidelines have been developed to support the efforts and are directly integrated in groundwater mapping and assessment activities. Databases have been established with the requirement that all collected data that is publicly funded or legislatively mandated be included, with free access to all. These databases include a wide range of data, including geological information, hydrological data, groundwater abstraction, water quality, geophysical surveys, geological modelling and groundwater modelling. The databases provide free and easy access to data through web portals and are continuously under further development for accessibility and to accommodate new data types and web services.

In South Africa, the programs with dedicated staffing are primarily for oversight and administration, with consultancies with high competencies working on a local scale. Guidelines supporting groundwater mapping and assessment have been produced but have not been fully integrated into mapping processes. Like in Denmark, national databases have also been established. However, not all state-collected data is uploaded to these databases and access to up- and download is only possible for the National Groundwater Archive (NGA) while data from other databases are available upon request. Groundwater related reports are not always centrally located, while no system is available for storing models for future reuse. The amount and structure for storing data may limit the public access.

As an important part of the Danish groundwater mapping program, a substantial funding was dedicated the development of specialised tools and approaches targeted the Danish conditions in terms of hydrogeological settings, the mapping and assessment purposes and administrative setup. Funding is similarly allocated groundwater research in South Africa, and while this has resulted in the development of tools specialized for South African conditions, the research supports broader aspects in water resource management.

4.3.4 Key characteristics

Even though there are significant differences in the Danish and South African approaches to groundwater mapping and assessment, there are still a number of key characteristics that are shared between the countries. These include:

- Both countries have national databases that are accessible to the public.
- Local and regional 3D geological and groundwater models are developed.
- Both countries actively co-interpret the different data types in the different groundwater mapping and assessment processes.

The difference in approaches also lead to differences between the two systems, particularly when you look at the details of the processes. The first difference lies in the expanse of data available in each country's databases. Although both countries have publicly accessible databases, the amount of data and results submitted to the databases varies (DK has 35 times more data point/sites per km^2 than SA). The data collected in Denmark is mandated to be submitted to the different databases, and this mandate is actively enforced. This includes all borehole-related data (geological, hydrological, pumping and water quality), geophysics and models. Data and results submitted to the databases in South Africa is not as expansive. Often, the data and results derived from groundwater mapping and assessment programs are collected by private consultants, and these results are considered proprietary information and not required to be shared. Much of the mapping and assessment in South Africa is also privately funded by the utilities themselves, and thus not required to share the data in the public databases.

In Denmark, 3D geological and hydrological models play a key role in both the protection and assessments of the sustainable groundwater resource to improve the system understanding and assess the sustainable groundwater use prior to the development of new wellfields. The widely use of models have made it possible to integrate the 3D models into a national model that covers nearly the entire country. It, however, needs to be emphasised that this is possible primarily because Denmark is a relatively small country with a fairly simple geological setting. In contrast, the models in South Africa are isolated local or regional models, predominantly used to assess the feasibility of a wellfield when the production wells have been established and pump tested executed.

Furthermore, 3D models are developed primarily to map out complex geological systems and with the highly varying geology throughout South Africa, the development of a national 3D geological model is much more ambitious.

Groundwater mapping and assessment in Denmark has been conducted using a standardised process. Even though the mapping and assessments have been conducted at the local and regional scale, the standardisation has allowed the results to be combined into a highly detailed national interpretation. In contrast, groundwater mapping and assessments in South Africa, carried out at the smaller scale, have not been integrated into a national interpretation. Mapping on the national scale is only conducted in a low detail, such as the national water resource map. The reason for this difference is in part due to the size of the country and the complexity of the hydrogeology across South Africa. In addition, the mapping activities, with a focus on finding new resources and development of new well fields, is conducted by the individual utilities using their own methods. Thus, without a standardised methodology, it is more difficult to combine the results into a national interpretation.

4.4 Factors supporting or impeding the South African approach

This section deals with factors supporting or impeding the groundwater mapping and assessment in South Africa. Identification of the impeding factors can highlight topics where a possible transfer from the Danish approach may be beneficial.

Surface water is historically and currently the main water resource in South Africa. Although groundwater is an important or the sole resource in areas where surface water is not available it is often seen as an unreliable secondary water resource. It has therefore only received minimal recognition, political support and funding for sustainable development and resource management. However, groundwater gained more attention through the development of various acts and strategies, which may potentially increase future support and enhance groundwater assessments such as groundwater mapping. Strategic groundwater use has been addressed in more recent water strategies, such as the National Groundwater Strategy that provides groundwater specific input to the National Water Resources Strategy, and by the inclusion of groundwater in the Strategic Water Resource Areas in 2018. Hence, groundwater is receiving a growing political attention, which are likely to increase the groundwater research and funding and thereby advancing the mapping and assessment.

Numerous good and valuable technical guidelines have been developed, however the use thereof is not mandatory, and it is not custom that projects request that the work should be aligned with the guidelines. The guidelines are furthermore not centrally accessible, which may limit their accessibility and knowledge about them. Hence, although clients may like the work to follow best practice as described in the guidelines, they may not be aware of them and thus not reference to them in the tenders.

Sufficient capacity among all actors is required to both request and conduct the assessments at a high technical level. Thus, the shortage of capacity and lack of knowledge at authoritative levels is expected to impact the quality of assessments, and a need has been identified to educate professionals in the water resource management discipline. The enhancement of knowledge through education will lead to the development and implementation of sustainable water management plans and an expected possible increase in groundwater utilisation. Raising awareness regarding groundwater related aspects among communities and interested people and stakeholders may promote participation in discussions without necessarily having the technical knowhow. Professional continuous development and capacity building of technicians will lead to high quality assessments on request.

Geophysicists with limited hydrological knowledge often perform geophysical investigations which means that geophysical data is often not properly analysed in the mapping of groundwater aquifers. Different geophysical methodology and instrumentation are better suited for different geological settings. During various projects the use of unsuitable methods are not uncommon. This is mostly due to financial constraints, unavailability of specific instrumentation and/or limited knowledge of which instrument will be most suitable for a specific geophysical investigation. Geological logs are seldom kept by local drillers. A geologist, trained technician or geohydrologist may do the logging themselves depending on the type of groundwater provision project and the client.

It is not mandatory to report data to a central entity and relevant data are stored in different databases at various levels, e.g. by national, regional, municipal entities or by consultants or customers. Data from the National Groundwater Archive (NGA) is freely available through a web portal, but several other national databases exist where direct access is not available to the general public. Data, digital maps and shapefiles can be obtained free of charge from DWS, while hard copy maps can be procured by DWS at a cost. Other data and maps are often not freely available and must be purchased from relevant government departments, South African Weather Services and from the Council of Geosciences. Similarly, access to databases held by other parties may be difficult and involve payments. The lack of compulsory reporting of data to a central entity with free and easy access creates a barrier towards the reuse of data. Where data exists, but are unavailable, the result will be either the collection of new data in the same area, or that data will not be included in the mapping and assessment. Hence, the assessment will be either more expensive that needed be, or the basis for the assessment will be poorer.

5. RECOMMENDATIONS

As groundwater mapping and assessments can be performed for various purposes, different steps and activities may be relevant. Many different flowcharts on conducting mapping and assessments can be developed. It is beyond the purpose of the current project to develop detailed programs for all types of assessments that are relevant for South African conditions. However, mapping is defined as activities related to the analysis and understanding of the groundwater system, while assessments use this understanding to conduct specific evaluations of the groundwater resources. The mapping activities are largely generic, i.e., something that has to be carried out irrespectively of the objective of the assessment. Hence, recommended steps and activities for groundwater mapping have been developed and described in Section 5.1. Assessments, on the other hand, are conducted for specific objectives, and hence recommendations for selected primary types of assessments in South Africa are presented in Section 5.2.

5.1 Recommendations for groundwater mapping

Recommendations for steps and activities to be included in groundwater mapping in South Africa are shown in Table 4. Depending on the complexity of the mapping project, not all activities may need to be performed for all projects. For each activity, it is specified if a task should be carried out based on the complexity level of the project. The complexity level relates both to the complexity of the physical conditions, i.e., the geological/hydrogeological settings, and the overall complexity of the project, often dependent upon the size/funding as well as how critical it is to meet the demands and the numbers and type of stakeholders. For projects with exploration for new groundwater abstraction, a low complexity refers to groundwater development for water supply on private properties where it is not necessary to apply for authorisation, i.e., mainly Schedule 1 use. Medium complexity is linked to groundwater developments that will not have a large impact and may only require a General Authorisation. The high complexity level is linked to wellfield developments and other groundwater use that has the potential to have a large impact. This last category will require a Water Use License with the requirement of a detailed hydrogeological report.

Table 4 provides and overview of the generic mapping steps and activities, which are detailed further in the sections below the table. The recommendations comprise two "levels" of recommendations: 1) recommendations on steps and activities to include while undertaking groundwater mapping, and 2) recommendations for supporting groundwater mapping, i.e. how to strengthen the mapping process by further developing the supporting infrastructure. While the first category can be enforced at the project level, e.g. by the clients, the second category are topics that need to be developed at the national level. Both types of recommendations are provided below, starting with recommendations related to the steps and activities.

Table 4. Recommendation for steps and activities for groundwater mapping in South Africa.

Steps and Activities		Complexity Level		
		Low	Medium	High
1. Desktop study				
	1.1 Collection of data from data bases reports		X	X
	1.2 Consultation of maps and aerial photos	X	X	X
	1.3 Reports and other publications on previous studies		X	X
	1.4 Gap analysis	X	X	X
	1.5 Stakeholder identification		(X)	X
	1.6 Inception report			X
2. Filling the gaps				
	2.1 Hydrocensus		X	X
	2.2 Collecting new data	X	X	X
	2.3 Baseline monitoring		X	X
	2.4 Stakeholder engagement		(X)	X
3. Modelling				
	3.1 Developing a conceptual model		X	X
	3.2 3D geological modelling			X
	3.3 Hydrostratigraphical modelling			X
	3.4 Geochemical modelling			X
	3.5 Flow modelling/Hydrological modelling			X
	3.6 Mapping (producing actual 2D maps)			X

STEP1: Desktop study

A desktop study consists of collecting all available data without going to the field. This includes the collection of data from databases and reports, which is then analysed to get a basic conceptual model of the groundwater conditions of the area. Maps and other GIS data/information showing the topography, geology and hydrogeology, as well as aerial photos can be used to develop a basic conceptual model of the groundwater systems. Reports and other publications about the study area can also be consulted to improve on the understanding of local groundwater conditions. The information is incorporated into a gap analysis that provides a framework of where information is lacking and where it will thus be necessary to carry out further investigations.

The last two activities, stakeholder identification and inception report, are recommended for all high complexity level projects. Involvement of stakeholders should further be considered for medium complexity level projects. Stakeholder identification at this early stage may help to identify people with the relevant information and may be able to ensure buy-in for the project. It is advisable to write an inception report to document all the relevant findings, the gaps identified and the stakeholders that will be invested in the project.

Recommendations for supporting groundwater mapping

Greater accessibility to data (geophysics, monitoring data, geology, etc.), relevant reports and maps may increase successful groundwater development. It is thus recommended that data collected in publicly funded projects be available to the public at no cost, that data be stored in central databases that are easy to access and use, and that these databases should include geophysics. It also recommended that data already stored centrally in hard print reports in the library "GH Report system" are digitised and that data are harvested and captured onto the NGA. Similar to study reports, a standardised storage of models, geological, hydrostratigraphic and flow models, should be considered, which will make the reuse and combining of models possible, potentially saving many resources. A common naming convention of boreholes and groundwater related information, including geophysics, could improve data accessibility.

STEP2: Filling the gaps

The gaps in understanding of the groundwater characteristics of a study area can be filled in a number of ways. The first, and most basic is the hydrocensus. During a hydrocensus, information is collected in the field about dug wells, boreholes and possible surface water – groundwater interactions, such as wetlands, pans, etc. This helps to determine general depth of boreholes, water strikes, water quality, groundwater – surface water interaction and groundwater dependent ecosystems.

The collection of new data includes doing geophysics, drilling new boreholes, doing yield tests and water quality analysis. Yield testing of existing boreholes under the Groundwater Resource Information Project (GRIP) is carried out to collect additional information before new boreholes are drilled (www.griplimpopo.co.za). A multitude of different geophysical methods are available and can be used for different purposes in different hydrogeological settings. For each study, the hydrogeological settings should first be considered in choosing an adequate method. Next the level of detail/resolution of the method should be considered. Methods like aerial electromagnetic surveys have the advantages of being able to cover large areas, which may be required in development of large wellfields, where water is withdrawn from a large area and the impacted area therefore can also be large. However, other methods offer a higher resolution in the data, which may be needed in very complex settings. For small developments, low complexity projects with limited abstraction, the spatial coverage is often less important, and focus should be to obtain very local information used for the local siting of boreholes.

Baseline monitoring should be carried out where the development of new wellfields, or expansions hereof, may potentially have a negative impact on the environment or existing activities. It may consist of only an initial water level that is measured or an extensive monitoring program that is carried out over a number of years. It is recommended that baseline monitoring be done before groundwater developments become operational. The ideal would be to have monitoring data for a year, but this may not always be possible or necessary. This will provide some measurement on which to base mapping and assessment, as well as future management of the resource.

A plan for the stakeholder involvement should be developed based on the size/complexity of the abstraction and the number and type of stakeholder involved. The ideal is to have regular stakeholder engagement with the relevant role players, as it could reduce friction between different groups and enhance the outcome of a project. One option is to include stakeholders in monitoring committees. While a monitoring committee do not have formal responsibilities or power, it has often been a successful platform for exchanging information with the stakeholders and for the stakeholders to put forward recommendations that might be taken up for improved development and management of the groundwater mapping and assessment.

Recommendations for supporting groundwater mapping
There is a need to develop guidelines that will recommend the best possible geophysical method that will provide the best results for a given geology and for the development at hand. Methods that rely on different electric and magnetic characteristics of geological formations may not be very successful in primary aquifers. In addition to identifying the optimal methods, the interpretation of data also deserves more attention in order to optimally utilise the data to assess the hydrogeology of the system. There is a need for further developing the skills for interpreting geophysical data with focus on hydrogeological properties. Furthermore, there is a need for developing central databases to store geophysical data.

Drilling is a very important part of groundwater development and should be done to the highest standard. It provides very important information about the subsurface geology and hydrogeology. It would thus be important to require compliance to available guidelines, and where necessary, to develop new guidelines. Currently, almost 100,000 wells are drilled annually, but only a small part of data from these boreholes are being shared, resulting in an immense lack of utilisation of existing data. Hence, sharing of data is an additional requirement which should be placed. This could, e.g. be executed by setting up a system where new drilling permits for drilling companies are only issued if data from previous jobs have been uploaded to relevant databases.

Several guidelines have been developed for various aspects related to groundwater mapping and assessments. Guidelines are, by nature, guiding principles based on best practise that allow for some flexibility in its implementation, which is necessary as all groundwater projects are unique. However, experiences show that existing guidelines only to a very limited extent are used in practise. There is hence a call for a mechanism to encourage the use of guidelines. This could include a requirement to use the guideline as part of the tendering process, e.g. starting with publicly funded projects.

STEP3: Modelling
A conceptual model should be developed based on available information and updated as new data and information become available. When flow modelling is included in the study, a conceptual model is developed for both the geological and hydrogeological understanding of the system. A conceptual model is used to establish an understanding of the groundwater system and identify what is most important and what needs the most attention during the entire process. It is a semi 3D model, that looks at the connectivity between aquifers, surface water and the environment that must be evaluated, even though the area of the study site must be limited. It forms the basis of other models but may itself be reformulated based on the results of the other modelling activities.

Detailed 3D geological modelling is often reserved for the most complex geological systems in a South African context, but experience gained through the modelling projects for Ladysmith and Saldanha Bay Local Municipality, as well as the work done for the City of Cape Town show that it can add valuable information to contribute to the understanding of hydrogeological systems. The development of these models should occur at an early stage in the process to aid in the understanding of the physical system.

Hydrostratigraphic modelling is currently not carried out as a separate activity in South Africa. It is, however, important to recognise that geological modelling may not necessarily focus on the water bearing features of the different sediments/bedrocks but may be interpreted based on geologic formations, which can have widely different hydrological properties even within the same formation. This can be, for example, fractured horizons within a formation. In addition, geological models are often complex, where as a hydrostratigraphic model can be useful in grouping the units with similar hydrological properties providing a simpler model which is easier to implement into a groundwater model. It is therefore recommended that the geological modelling is supplemented by considerations on hydrostratigraphy, either through an independent interpretation, or by including the hydrological aspects in the geological modelling.

Geochemical modelling is currently mostly used for contaminated sites, but could be used to determine flow paths, gain an understanding in water-rock interactions and other groundwater processes. It is thus recommended that geochemical modelling is considered and encouraged in areas where the groundwater quality varies and the chemical components of the aquifer can aid in the understanding of flow processes.

Hydrogeological/flow models are often only used for larger groundwater developments or activities that may have a significant impact on the groundwater resource or surface water systems, e.g. groundwater dependent ecosystems. An important benefit of modelling is that the model combines all available knowledge and data for the area, and by comparing the model results with field observation the model's accuracy can be assessed. Small discrepancies between observation and model results indicates that a good understanding of the system and its dynamics have been obtained. On the other hand, large discrepancies indicate that more information/data is required. The model can thus be used actively in the development of the system understanding. With the final model it is further possible to assess the sustainable yields, i.e. what is the quantity that can be pumped without causing and unacceptable impact on the nature, e.g. groundwater depending ecosystems. It is therefore recommended that flow models are developed for projects that can potentially have a large impact on the surrounding environment. It is particularly recommended for layered systems, where multiple aquifer system interact. Flow models, especially integrated groundwater/surface water models, are also recommended where the potential impact from groundwater abstraction on other parts of the water cycle such as wetlands, rivers, and lakes, may be significant and where there is a need for this impact to be quantified. Finally, flow models are recommended for projects where possible impacts from abstraction are especially critical. The adequacy of 3D flow models should, however, be evaluated in each case by considering available data/knowledge and the complexity of the system. Development of 3D flow models may be very challenging when a groundwater system is related to discrete features, i.e., fractures/dykes etc. with no interaction with the bedrock matrix. Detailed data and knowledge are required to fully understand and capture such systems in 3D flow models. If data do not support such comprehensive understanding, the use of a 3D flow model may be less valuable.

Recommendations for supporting groundwater mapping

It may not be possible – or necessary – to develop models for the whole country, and it may be necessary to focus on a number of priority areas. The current use of models in South Africa is generally limited to the development of wellfields and other higher impact activities. It is, however, a valuable investment into regional groundwater mapping and the subsequent management of the resource. A large amount of data – including geophysical data – that can be used in the development of geological models is available and has been interpreted by local consultants. One of the gaps that has been identified during this project is that there is a need for this data to be compiled to provide a coherent understanding of groundwater resources. The size and complexity of the South African geology may make the development of a national scale model, similar to the model developed for Denmark unfeasible. It would, however, be possible to develop models that can be integrated on a regional scale, if the work has been done to a similar standard and within a common format. To fully exploit the existing knowledge and data at larger scales, it is thus recommended to study the possibility of developing common frameworks for geological/hydrostratigraphic modelling in South Africa in relation to groundwater assessments. With the highly varying geology in the country, it is not envisioned feasible to develop one common framework for the entire country, but instead developing frameworks for different parts of the country with comparable hydrogeological setting, starting out with strategic areas.

Guidelines may help to provide directions on the type of modelling required for site specific situations and level of impact or complexity. It should also provide standards that can be used to ensure that all models are done to high standards ensuring confidence in the results, to make it possible compare models and to integrate local scale models into regional models at a later stage.

5.2 Recommendations for groundwater assessments

Different types of assessments have been identified for which the primary purposes are:

- Wellfield development, e.g., the assessment of where and how much water is available to support a single well or a wellfield. This type of assessment widely varies in terms of scale and complexity, ranging from backyard drilling to development of large municipality wellfields.
- Resource quantification and allocation. This type of assessment has been carried out at national scale to assess aquifer characteristics and groundwater availability at national scale, this has, e.g., been accomplished through GRAI and GRAII.
- Protection. Areas with high production of the water resource, either surface or groundwater, have been identified from which Strategic Water Source Areas (SWSA) have been delineated. To secure the water resource, assessments are carried out to protect the SWSA.

Recommendations related to the three different types of assessments are described in the section below.

5.2.1 Assessments for wellfield development

The most common type of assessments carried out in South Africa is exploration for a new water supply. Most experience thus exists for these types of assessments, and most people are similarly involved in such assessments. Acknowledging this, the recommendations on steps and activities for mapping carried out in relation to wellfield development are included in

Table 5. This is a slightly expanded version of the description provided in section 5.1 and includes mapping activities specifically targeted towards the assessment of developing new well/wellfield.

When the mapping activities have been completed, the results are used to assess the available groundwater resource, consisting of tasks listed in Table 6 and described in the accompanying text. While listed here as consecutive activities, it must be acknowledged that the mapping and assessment include iterations/loops. In addition to the mapping and assessment activities described below, a number of other steps are part of the development of wellfields, e.g. administrative, legal and planning tasks, and may further involve loops in the entire process. These activities are not covered in the current project.

Table 5 Recommended groundwater mapping steps and activities related to wellfield development.

Steps and Activities	Complexity Level		
	Low	Medium	High
1. Desktop study			
1.1 Collection of data from data bases reports		X	X
1.2 Consultation of maps and aerial photos	X	X	X
1.3 Reports and other publications on previous studies		X	X
1.4 Gap analysis	X	X	X
1.5 Stakeholder identification		(X)	X
1.6 Inception report			X
2. Filling the gaps			
2.1 Hydrocensus		X	X
2.2 Collecting new data	X	X	X
2.2.1 Test pumping existing boreholes			X
2.2.2 Geophysics and borehole siting	X	X	X
2.2.3 Drilling (E – exploration)		X	X
2.2.4 Test pumping new boreholes	X	X	X
2.3 Baseline monitoring			X
2.4 Stakeholder engagement		(X)	X
3. Modelling			
3.1 Developing a conceptual model	X	X	X
3.2 3D geological modelling			X
3.3 Hydrostratigraphical modelling			X
3.4 Geochemical modelling			X
3.5 Flow modelling/Hydrological modelling			X

Step 1 – Desktop study:

The activities under the desktop study are similar to that of the general mapping exercise described in Section 5.1, but will be more focused on determining whether the groundwater system will be able to provide the yield needed to make it economically viable for the development of a wellfield. The objective of the mapping and assessment is to apply for an abstraction license, which will consider not only the yield of the aquifer, but also how the abstraction may potentially impact natural systems depending on groundwater. Hence, the desktop study will also include an identification of potential vulnerable systems that may be affected by the pumping.

Step 2 – Filling in the gaps:

The activities under step 2 are also similar to that of the general mapping, but again with focus on collecting new data from which availability and yield of the groundwater resource can be estimated. This is reflected in

Table 5 that provides more detail about the activities recommended under 2.2 Collecting new data. This includes geophysics, yield tests and drilling of exploration boreholes. During baseline monitoring, it is not sufficient to establish monitoring data for evaluating aquifer yields. The monitoring should additionally be targeted towards potentially vulnerable locations to establish data for a pre-abstraction period, to which groundwater levels during abstraction can be compared.

Step 3 – Modelling:
Most of the activities related to modelling are identical for a general mapping activity and mapping related to wellfield development. As for the previous steps, the focus will again be on the possible production from the aquifer. This may include considerations on how uncertainty in the geological/hydrological understanding may impact the estimated groundwater resource, and if there is a need to include alternative interpretations of the subsurface to quantify this uncertainty.

The mapping activities above provide an understanding of the groundwater system with specific focus on data and knowledge related to groundwater abstraction, including identification of vulnerable areas where potential impacts from abstraction must be followed and assessed. Once the basis has been established, it will be utilised to assess and quantify the amount of water that can be abstracted, which is carried out by the steps listed in Table 6.

Table 6. Recommended steps and activities related to assessments for wellfield development.

Steps and Activities	**Complexity Level**		
	Low	Medium	High
1 Feasibility	X	X	X
2 Modelling			X
3 Exploration and monitoring		X	X
4 Assessment Report		X	X
5 Stakeholder engagement			X

Step 1- Feasibility
It may be argued that the entire assessment process is a feasibility study in which the potential and sustainable yields are assessed, i.e. how much can the aquifer potential deliver, and how much can the aquifer deliver without resulting in an unacceptable impact on the environment. Here we define the feasibility study loosely as the initial assessment of whether the aquifer can produce the quantity of water required. This corresponds to the Reconnaissance level by Riemann et al (2011), being the first step of a groundwater assessment. Hence, a feasibility study is carried out initially for all wellfield development projects. The outcome of the feasibility study and the complexity level will determine the next steps. For low complexity projects, such as schedule one wells, it may be sufficient to document that existing boreholes in the area are producing well and move on to the actual drilling of the well. Where a higher degree of certainty is needed, the mapping activities will be engaged to provide a more comprehensive understanding of the system and the potential yield.

Step 2 - Modelling
Geochemical modelling is used to evaluate the groundwater quality in the area prior to the establishment of new abstraction boreholes and well fields. The information on the groundwater quality is needed to determine the viability of the groundwater for the needed purpose. It will also provide information on the need for protective measures that need to be taken to assure the long-term sustainability of the new groundwater abstraction.

The flow modelling is applied to estimate a sustainable yield, i.e. the groundwater quantity available for abstraction. This involves two aspects: 1) assessing the acceptable impact of the pumping on the surrounding area, and 2) how much can be abstracted without exceeding this impact. The acceptable impact can be set by defining specific criteria that cannot be violated, such as a maximum drawdown of the groundwater heads, a maximum reduction of groundwater flow to river systems etc. These criteria are in generally set based by weighting the effect of the impact against the need for groundwater abstraction. Once the criteria have been established, the flow model is used to estimate the sustainable use, which is the maximum amount of groundwater that can be abstracted without violating the criteria. In practice this is obtained by simulating a number of scenarios with different pumping rates and alternative locations of abstraction wells, from which the impacts are calculated as the differences between the scenarios and the baseline situation, e.g. with no abstraction.

Step 3 - Exploration and monitoring
Monitoring, development of exploration wells and yield tests may be included in the mapping activities and further developed during the assessment. In the development of a monitoring program, considerations should be given to the requirements for the authorisation and management processes with respect to water levels, water quality sampling and chemical analysis.

Step 4 – Assessment report
Results from the assessments should be described in an Assessment Report in a form that can provide basis for issuing permits, and that provide information relevant to the stakeholders involved. The report should be made accessible for other studies to maximise the reuse of data and subsurface understanding.

Step 5 - Stakeholder engagement
Stakeholder engagement is represented in Step 1 (1.5 Stakeholder identification) and Step 2 (2.4 Stakeholder engagement) and should similar be included during the assessment. It is mostly required for high-level developments and should involve more than just informing the public about the outcomes of a development. The ideal would be to involve stakeholders throughout the process to insure higher buy-in and adoption of the projects.

5.2.2 Assessments for resource quantification and allocation

The groundwater assessments programmes GRA I and GRA II were carried out as part of the national water resource planning with estimation of the groundwater availability at the national scale as described above. Currently, the follow up programme GRA III is under development, where a central topic will be to utilise data, knowledge and assessments from previous small to large scale groundwater studies undertaken throughout the country.

Combining different studies presents several challenges. A crucial issue is to ensure that the type of results from the different studies are interchangeable and thus can be compared and combined. Depending on the specific goals, the approaches used, and the clients and consultants involved, the results from two projects may be worded equally but have different meanings. In groundwater assessments, typical examples include groundwater recharge/net-precipitation/infiltration and sustainable yields. In the first case the words may be interpreted differently and thus used for different quantities in different studies, while sustainable yield is not a physical quantity, but needs to be defined based on some accepted impact from groundwater pumping on the environment. Without a strict terminology, great care must thus be taken when results from different studies are combined.

Other vital topics for the reuse of study results is the ability to evaluate the quality and uncertainty associated to the results, as well as their expected representativeness, i.e. whether the results are expected to represent local conditions only, or can be extrapolated to a larger area of similar settings. While such aspects are addressed by some studies, it has to be extracted from reports in other cases, which, depending on the reporting, may not always be possible.

A third type of topics making the combination of previous studies challenging is that different studies often operate with different conceptual understandings of the subsurface. Estimates of e.g. storage or aquifer yields in local studies may focus on local aquifer systems, while national studies are targeting regional aquifer systems. Correlating results from studies carried out at different scales with different aims, may thus require a common conceptual reference framework to understand the interrelationships between groundwater units. Such a framework would further support the use of existing data in the interpretation and understanding of the subsurface systems beyond the individual study boundaries.

To support the reuse of results from specific studies in national assessments it is recommended to further develop:

- National terminologies within groundwater mapping and assessments that will ease the reuse of results from individual studies by clearly defining the various quantities and thereby minimising the risk for combining dissimilar result types.
- National standards and guidelines. Standards are needed to ensure the quality of the work by setting some minimum requirements and will further aid to the transferability of the results between projects. Standards may also include requirements on the reporting and storage of data, reports and results making it readily available. As each study is unique and require different approaches, guidelines need to support standards with recommendations that should be considered. Suggestions to specific guidelines are provided in the section above.
- Development of common conceptual frameworks for geological and hydrostratigraphic interpretation related to groundwater mapping and assessments. With the highly varying geology in the country it is not envisioned feasible to develop one common framework for the entire country, but instead developing frameworks for different parts of the country with comparable hydrogeological setting, starting out with strategic areas, such as the SWRA for groundwater and CMA with existing or developing need for municipal supply.

The specific contents of the standards and guidelines, as well as the development of a conceptual hydrogeological framework will vary with the varying challenges and/or physical settings. It may thus be considered to develop these based on experiences from existing projects and tested and modified through application on a number of pilot sites. Sites with different geology and hydrogeology should be selected, as the methods may have to be adjusted for each site. Langebaan Road (regional coastal aquifer), Beaufort West (fractured aquifer) and Ramotswa (karst aquifer) are potential sites, with a large amount of data available and airborne geophysics have been carried out for two of the three sites.

5.2.3 Assessments for groundwater protections

One of the primary focuses of the Danish Groundwater Mapping and Assessment program is on the protection of the existing groundwater resources. In Denmark, this focus has been in the areas with special drinking water interests as well as the well field catchment areas outside of these interests, comprising just over 40% of Denmark's land area. With intensive agriculture covering much of this area, the assessment in Denmark has a focus on nitrate and pesticide pollution. This is in contrast to South Africa, where in addition to agricultural sources, pollution from mining and other industrial sources also impact groundwater quality. Although there are differences between Denmark and South Africa, both in the size (see Figure 40) and geological complexity as well as the different threats to the groundwater quality, there are still aspects of groundwater mapping and assessment program in Denmark that can be effectively applied in groundwater protection in South Africa.

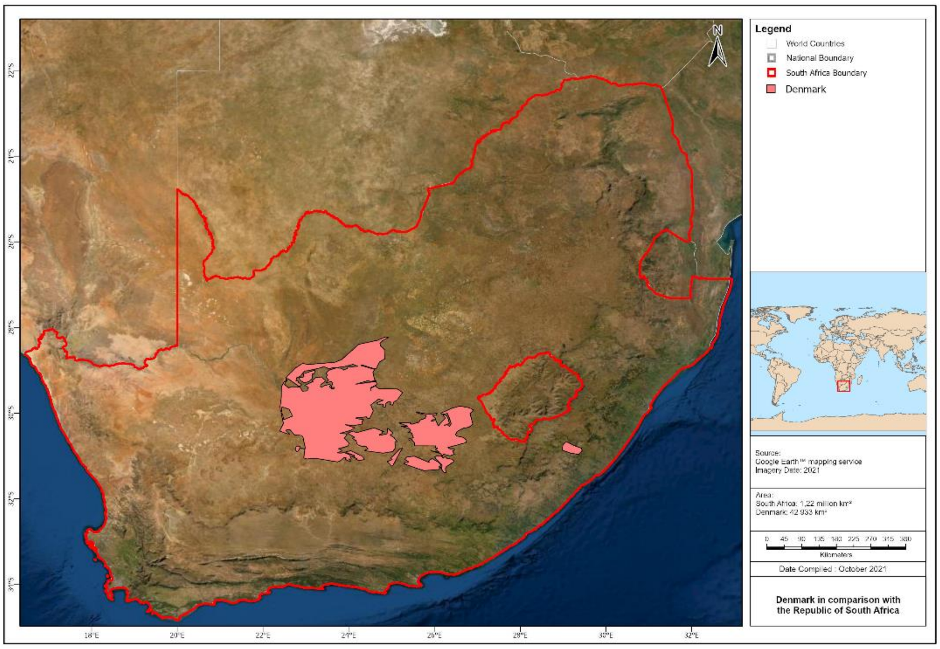

Figure 40 Map showing the relative size of Denmark compared to South Africa.

In Denmark, the groundwater vulnerability assessments are done on a local to smaller regional scale (maximum 1,000 km^2). The foundation of the vulnerability assessments rest in the detailed geological, geochemical and groundwater modelling. This includes detailed mapping of the thickness of the aquitards (predominately clayey sediments and shale) that act as protective layers over the groundwater aquifers, identifying the groundwater chemical processes, as well as calculating the well field catchment areas with a 200-year groundwater travel time and the well head protection areas.

As stated above, South Africa has a much larger area than Denmark, and conducting detailed vulnerability assessments over all areas of special drinking water interests will be an ambitious undertaking. However, in situations where the resource is important and the complexity level is high, detailed vulnerability assessments can be advantageous. This could be, for example, related to protecting municipal water supply well fields. In these high complexity level cases, as shown on Table 4, it is recommended that a groundwater flow model is created. From this groundwater model, the well field capture zones can be mapped and the different threats be assessed (i.e., agricultural or mining pollution) and relative hydrogeological vulnerability in these areas determined. Thus, the vulnerable areas can be identified and protective efforts can be focused in these areas. The vulnerable areas can furthermore be prioritized after model calculated transport time from the surface to the production well, where areas with the shortest transport time are prioritised higher than those with a longer transport time.

In addition to the well field capture zones, it is also important to protect the area around production wells – a so-called well head protective zone. It is important to protect drinking water wells against pollution from, for example, chemical spills or agricultural pollutants from flowing directly into the well or along the well casing to the aquifer. This could be similar to what is done in Denmark, where a 10-meter protection zone around all municipal drinking water wells is established. In these zones, no activities that could result in the area being polluted are allowed. As this is a relatively simple but important measure to implement in order to protect the water supply, it is recommended that a 10-meter protective zone be established around all municipal water supply wells.

5.3 Additional recommendations

Section 5.1 and 5.2 includes specific recommendations for steps and activities associated to groundwater mapping and assessments, both recommendations that can be readily implemented and longer term recommendations for improving the supporting infrastructure for mapping and assessments. The analyses and interviews carried out during the current project revealed additional topics that have influenced the mapping and assessment approaches in the two countries. These are briefly summarised here for a concise overview and organised according to the identified key factors. Recommendations are provided for technical topics, which are based on the comparison with the Danish approach. In addition to the technical aspects, some observations have been made related to the Institutional - Policy setup. However, it is out of the scope of the current project to make recommendations on these topics, which have thus only been listed for completeness.

Institutional – Policy

- The Danish groundwater mapping and assessment approach is deeply rooted in policy, with political ambitions on securing current and future groundwater resources and providing mandate for protection and the collection of levies earmarked to groundwater mapping. The development and protection of groundwater in Denmark is thus highly prioritised and supported by policy. In South Africa several national strategies and initiatives have been developed in the past decade providing political ambitions but does not receive an equivalent support in the political system.

Supporting infrastructure

- Competences and capacity
    - It is recommended that focus is put on capacity building among all actors involved in groundwater mapping/assessments and management to foster an environment with high technical competences which can ensure a high technical quality.
    - Additionally, capacity building should be broadened to include awareness raising among the public to develop a general understanding of groundwater and the qualitative and quantitative vulnerability of the resource.
- Guidelines
    - Several guidelines exist but their use is limited. It is recommended that a structure and mechanism for enhancing the use of guidelines are put in place. This could, e.g., be executed by making it mandatory that consultants relate their proposed project solutions to national guidelines.
    - If guidelines are to be better integrated, it is necessary that the clients similarly are aware of these guidelines and know the latest version. For this a better dissemination to professionals in the field is necessary, as is a central access to guidelines providing the newest version.

Key Characteristics

- Modelling
    - Several local/small scale geological interpretations already exist but have not been combined for an improved large scale understanding. It is recommended to analyse whether or not frameworks can be developed in which existing interpretations can be incorporated to provide larger scale interpretations.

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